SERVO SYSTEMS AND DATA TRANSMISSION

United States Government Printing Office
Washington : 1952

DEPARTMENTS OF THE ARMY AND
THE AIR FORCE
WASHINGTON 25, D. C., *22 August 1952*

TM 11-674/TO 16-1-277 is published for the information and guidance of all concerned.

[AG 413.44 (3 Jul 52)]

BY ORDER OF THE SECRETARIES OF THE ARMY AND THE AIR FORCE:

OFFICIAL:
WM. E. BERGIN
Major General, USA
The Adjutant General

J. LAWTON COLLINS
Chief of Staff, United States Army

OFFICIAL:
K. E. THIEBAUD
Colonel, USAF
Air Adjutant General

N. F. TWINING
Acting Chief of Staff
United States Air Force

DISTRIBUTION:

Active Army:

Tech Svc (2); Tech Svc Bd (1); AFF (5); AFF Bd (ea Svc Test Sec) (1); AA Comd (2); OS Maj Comd (25); Base Comd (3); MDW (5); Log Comd (2); A (25); CHQ (2); FT (2); Sch 5, 6, 7, 17 (25); PMS&T 11 (1); Dep (2) except 11 (20); RTC (2) except 11 (100); POE (2), OSD (3); Mil Dist (3); T/O & E's: 11-57N (2); 11-95 (2); 11-537T (2); 11-547 (2); 11-617 (2).

NG: Same as Active Army.

ORC: Same as Active Army.

For explanation of distribution formula, See SR 310-90-1.

ELECTRONIC FUNDAMENTALS SERIES

The manuals on electronic fundamentals form a progressive series of educational texts which present the theory and application of electronics for the military services. The series starts with the basic electrical fundamentals and extends to the most recent technical concepts, as applied to telegraphy, telephony, radio, loran, facsimile, radio direction finding, radar, meteorological radio, television, and other military equipments. For available manuals in the series, see SR 310–20–4.

CONTENTS

		Paragraphs	Page
CHAPTER 1. INTRODUCTION			
Section I.	General	1–3	1
II.	Control systems	4–7	2
III.	Representative military applications of servos	8–10	6
CHAPTER 2. BASIC SERVO PRINCIPLES			
Section I.	Elementary positioning servo	11–14	8
II.	Stability considerations	15–17	12
III.	Error considerations	18–22	14
IV.	Over-all response	23–26	19
V.	(Simple) rate servo	27–34	21
VI.	Relative merits of different control methods	35–37	23
VII.	Modified error signals	38–41	23
VIII.	Mechanical problems	42–44	24
CHAPTER 3. SERVO COMPONENTS			
Section I.	Actuators	45–51	26
II.	Controllers	52–59	38
III.	Auxiliary elements preceding controller	60–65	47
IV.	Basic sensing elements	66–68	57
V.	Synchros	69–77	59
VI.	Resolvers	78–84	69
VII.	Potentiometers	85–89	74
VIII.	Other sensing elements	90–93	78
IX.	Other elements	94–98	79
X.	General considerations	99–101	81
CHAPTER 4. EXAMPLES OF SERVOS AND SERVO SYSTEMS			
Section I.	Automatic temperature-control servo system	102–106	84
II.	Compass repeater servo	107–108	86
III.	Antiaircraft tracking radar	109–113	87
IV.	Analogue computation	114–115	95
V.	Antiaircraft predictor	116–127	96
CHAPTER 5. LONG-DISTANCE DATA TRANSMISSION			
Section I.	Requirements for long-distance data transmission	128–130	106
II.	Basic problem	131–133	106
III.	Synchro-data transmission over voice channels	134–136	107
IV.	Pulse-code modulation	137–144	108
INDEX			115

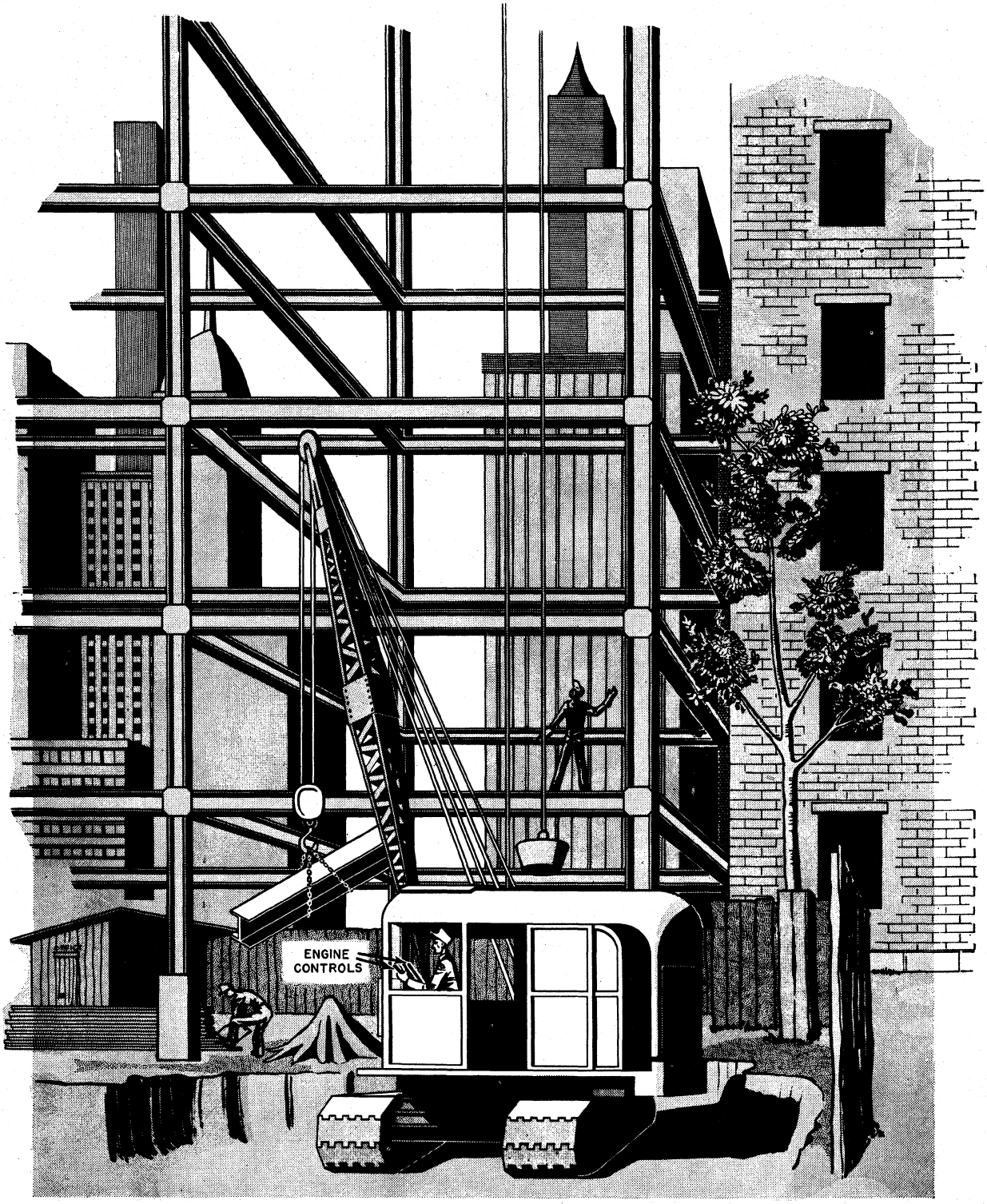


Figure 1. Control system to assist operator to raise heavy load.

TM 674-1

CHAPTER 1

INTRODUCTION

Section I. GENERAL

1. Shaft Setting

a. The effectiveness of a modern military organization depends on the precision with which shafts can be set. A single example will illustrate this. To conduct a successful operation on land or at sea, reasonable security from bombing attacks is necessary. This involves, among other things, antiaircraft defenses. Consider the problem of knocking an enemy airplane out of the sky. The bearing, altitude, and range of the airplane must be determined with precision so that its position is accurately known. Next, the direction in which the airplane is moving and its speed must be determined by watching the way its position changes. Once the position, speed, and direction of motion are known, a point called the advance position must be computed. This is the point on the path of the airplane where a shell can be placed to meet it. Finally, a gun must be pointed so that the shell can be delivered to the advanced position at the right time. All of this computation is accomplished by means of a radar which determines the position of the airplane and presents it to the rest of the antiaircraft system in the form of shaft settings.

b. To visualize these shaft settings, imagine that each shaft setting carries a pointer, shown as a dial reading. These shaft settings are reproduced on the input shafts of an automatic calculating machine, called a predictor. The predictor makes use of the continuing flow of position information supplied by the radar to compute the speed and direction of the target; from these data, it determines the advance position and supplies the gun-pointing orders that will put a shell at the advance position at the right time. The gun orders appear as a different set of shaft settings on the output shafts of the predictor, and these settings are reproduced on shafts which indicate the actual direction in which the gun is to be pointed, so that it is aimed automatically. If the entire operation is carried out with precision, the shell will keep its date with the enemy plane.

2. Servo Systems and Data Transmission

A *servo* is a special type of automatic control, and a *servo system* may be described as a system involving one or more servos. In the antiaircraft system described above, radar data are passed from the radar to the predictor, and gun orders are passed from the predictor to each of the guns. Since the complete installation is spread out, it is imposible to provide direct mechanical connections to reproduce the radar shaft settings at the predictor, or the predictor output shaft settings at the gun. These are accomplished by *data-transmission systems* and servo systems. Each of the radar output shafts, for example, is connected mechanically to the transmitting end of a data-transmission system. This involves equipment which produces electrical signals that depend on shaft setting. These signals are sent along wires to the receiving end of the data-transmission system at the predictor. An automatic control system, or servo system, in the predictor compares the actual setting of the predictor input shaft with the setting called for by the signals at the receiving end of the data-transmission link. If the actual setting is incorrect, the servo system alters it to the correct one. The combination of data-transmission system and servo system allows the setting of one shaft, which may be called the transmitting shaft, to be repeated automatically at a number of other shafts, called receiving shafts. Since the data-transmission system may involve a radio link, the transmitting and receiving shafts may be separated by distances up to several thousand miles. Besides the advantages

of remote shaft setting, the combination allows great ease of control. The power required to move the receiving shaft is supplied by the servo system, so that the setting of the transmitting shaft may be changed with little effort. In some applications that make use of this power amplification, the two shafts may be separated by less than an inch. Servo systems, with or without extensive data-transmission systems, are used in many other places where automatic operation is required. For example, a servo system may alter the setting of aircraft control surfaces in response to orders from an autopilot; it may alter the pitch of an aircraft propeller automatically so that the engine speed is held at a desired number of revolutions per minute; or it may move the antenna of an automatic-tracking radar so that it always follows its target.

3. Purpose and Scope

The purpose of this manual is to acquaint the reader with the fundamental principles of servo systems and data-transmission systems. Basic understanding is emphasized rather than a detailed knowledge of any particular system or equipment, so that the reader will be able to understand the operation of any servo equipment he is likely to meet. This manual discusses two representative servos in some detail, describes two other servos and servo systems without going into great detail, and covers most of the servo components normally used. The final chapter discusses some of the problems of data transmission and introduces pulse code modulation as a method of transmitting information.

Section II. CONTROL SYSTEMS

4. Need for Control Systems

A human operator can accomplish certain actions, for example the driving of an automobile, better than any control system of reasonable size and complexity. In many actions, however, a control system can assist an operator to carry out his work faster or more precisely. An unaided control system may even be able to do the work. A servo is a special type of automatic control system.

a. Movement of Heavy Load. Frequently, an operator is required to control the movement of a load so heavy that the assistance of a control system is essential. In the example illustrated in figure 1, the control system involved consists of the hoisting engine and its operating controls. The crane operator cannot lift the load, which may amount to several hundred tons, without the assistance of the hoisting engine, but it is easy for him to operate the engine controls.

b. Precise Positioning. In certain cases, automatic control systems are used because they operate with greater precision than human operators. Figure 2 shows a ship-mounted radar that is supposed to point directly at its target, an aircraft, at all times. One or more operators sometimes position the radar antenna, either directly, by moving it manually, or with the assistance of positioning control systems; however, this is difficult since it is necessary to compensate continuously for the rolling and pitching of the ship. A much better job is done by automatic control systems that operate in response to changes in the output of the radar and require no human assistance.

c. Control of Nonmechanical Quantities. Consider the problem of heating a house. If the house temperature is too low, there is nothing a human operator can do to raise it, since he is limited to the performance of mechanical work, such as moving and lifting. With the assistance of a furnace, however, he can control the house temperature easily. The furnace is part of the temperature-control system which, like the hoisting engine, assists the operator to do a job he cannot do alone. The operator of the hoisting engine, however, is unable to lift the load only because it is too heavy for him. He is able to lift lighter loads and, in general, can do the same work as the hoisting engine. However, he is unable to heat a house without the furnace, even if it is only a small house. The control system in the first instance extends the existing capability of the operator; in the second, the furnace gives him a completely new capability. The control system, therefore, may replace the operator, it may supplement the ability of the operator, or it may give the operator completely new abilities.

d. Control at a Distance. Instead of assisting the operator to do a job he cannot do alone, the control system may aid him in doing it at a place

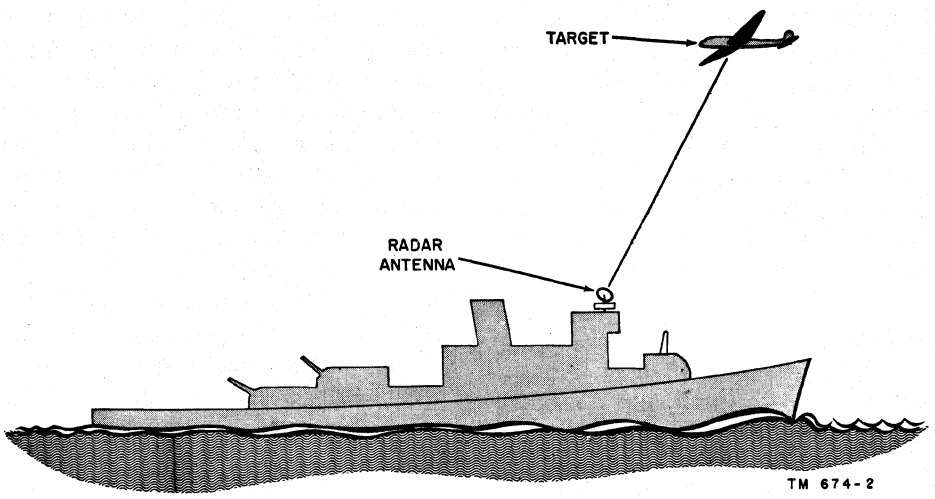


Figure 2. Automatic controls keep radar antennas pointed at target.

where he cannot do it without help. An example is the control system that changes the path of a guided bomb. The bombardier, who must remain in the aircraft, gives control orders that are sent over a radio data-transmission system to the bomb. Servos in the bomb then move the control surfaces in response to these orders. The complete control system, therefore, includes both automatic controls and a data-transmission system in the bomb, which act in response to the orders originated in the aircraft by the bombardier.

5. Open and Closed Control Systems

There are two basic types of control systems—open and closed. It is not always easy to make a fundamental distinction between these two basic systems; an open system may be part of a larger system that is closed, or a closed control system may be part of a larger system that is open. The distinction between the two systems lies in whether or not the action of the control is affected by the result of its earlier action. A system that operates only in response to external orders, paying no attention to the result of its action, is an open system. A system that bases its action both on external orders and on the behavior of the load or quantity that it controls is a closed system.

a. Open Control System. Assume that an engineer is in charge of a large steam-driven engine, the main driving engine of a ship. He is able to control the speed of this engine by adjusting a throttle that limits the amount of steam reaching the engine. Assume, further, that the engineer is unable to read the speed of the engine directly. He therefore makes a table of throttle settings, based on experience, that probably will give any particular engine speed. If the engineer receives a speed order calling for the engine to be operated at 90 revolutions per minute, he consults his table and makes the appropriate throttle setting. The throttle itself is an open control system, since the amount of steam it passes is governed by the setting and is not affected by the engine speed. The combination of throttle and engineer is also an open control system, since the amount of steam passed to the engine is governed by the throttle setting, and this is determined by the speed order that the engineer receives. The amount of steam will not be increased if the engine runs too slowly, nor will it be decreased if the engine runs too fast.

b. Open Control System With Repeat-Back. Suppose, now, that a tachometer is added to the engine room equipment. This is an instrument that indicates engine speed on a large dial. It is called a repeat-back because it reports the actual engine speed to the engineer. The throttle alone is still an open system, and the combination of throttle and engineer is also an open system if the engineer does not look at the tachometer. If, however, the engineer watches the tachometer and changes the throttle setting whenever the engine speed does not agree with the speed order, the system becomes a closed one. The amount of steam passed to the engine is governed by the speed order and by the engine speed, the engine speed being the controlled quantity.

c. Closed Control System. If the tachometer is connected to the throttle by an additional auto-

matic control system, the throttle can be adjusted automatically until the engine speed agrees with the speed order. This is a closed system. It is worth noting that the complete engine control system may be converted from an open control to closed control, either by the engineer watching the tachometer and making adjustments in the throttle setting when the speed varies from the speed order, or by an automatic device.

6. Definition of Servo

A servo is simply a control system in which the action of the controller depends both on the external order and on the behavior of the controlled quantity. It is important to understand this statement since it leads to an understanding of the whole behavior of a servo, which, in general, compares the actual value of the controlled quantity with the value called for by the external order, and then takes action in response to any difference between the two. This difference is called the servo error.

7. Examples of Servos

The following examples of servos are based on the problem discussed above, that of controlling the speed of an engine. The complete servo is shown in figure 3. The engine drives the tachometer, which produces a signal that indicates the engine speed. An external speed order is received by way of a data-transmission system which is not shown. A sensing element compares the actual speed with the speed order and develops a speed-error signal which is the difference between the ordered speed and the actual speed. This controls a throttle adjuster which alters the throttle setting and so affects the speed of the engine. The nature of the various signals is not important to the discussion at this point. What must be emphasized is the loop configuration of the complete servo, in which the speed error signal acts through the throttle adjuster and the throttle to alter the engine speed, which in turn alters the tachometer signal and changes the resulting value of the speed error. The over-all behavior of the system may be described by saying that the throttle is adjusted in such a way that the speed error is reduced to zero. The complete loop may be formed in a number of ways, some of which are discussed below.

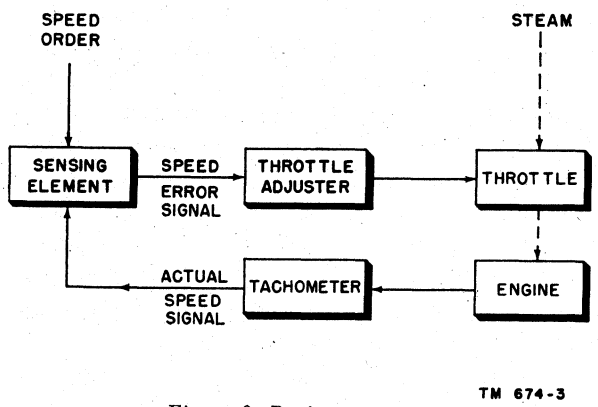


Figure 3. Basic servo loop.

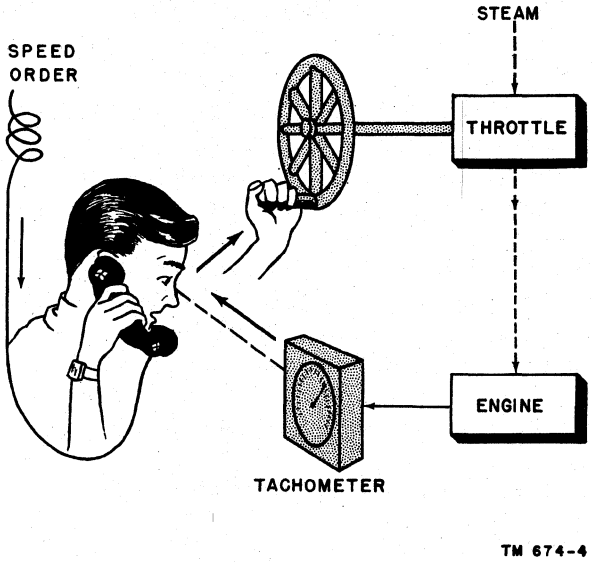


Figure 4. Basic servo loop with operator as sensing element.

a. Open Control System With Repeat-Back, Where Operator Is Part of Servo Loop. Without the engineer, this is an open control system with repeat-back, but if the engineer stays awake and closes the loop he makes it into a servo. In the operation of the system (fig. 4), the engineer receives a speed order by telephone, observes the actual speed by looking at the tachometer dial, and then makes an appropriate throttle setting. The engineer thus takes the place of both the sensing element and the throttle adjuster shown in figure 3.

b. Automatic Servo. In this system (fig. 5), a speed order is set on the sensing element, which is on the bridge of the ship. A remote-reading tachometer on the bridge of the ship provides an indication of the engine speed. This is received

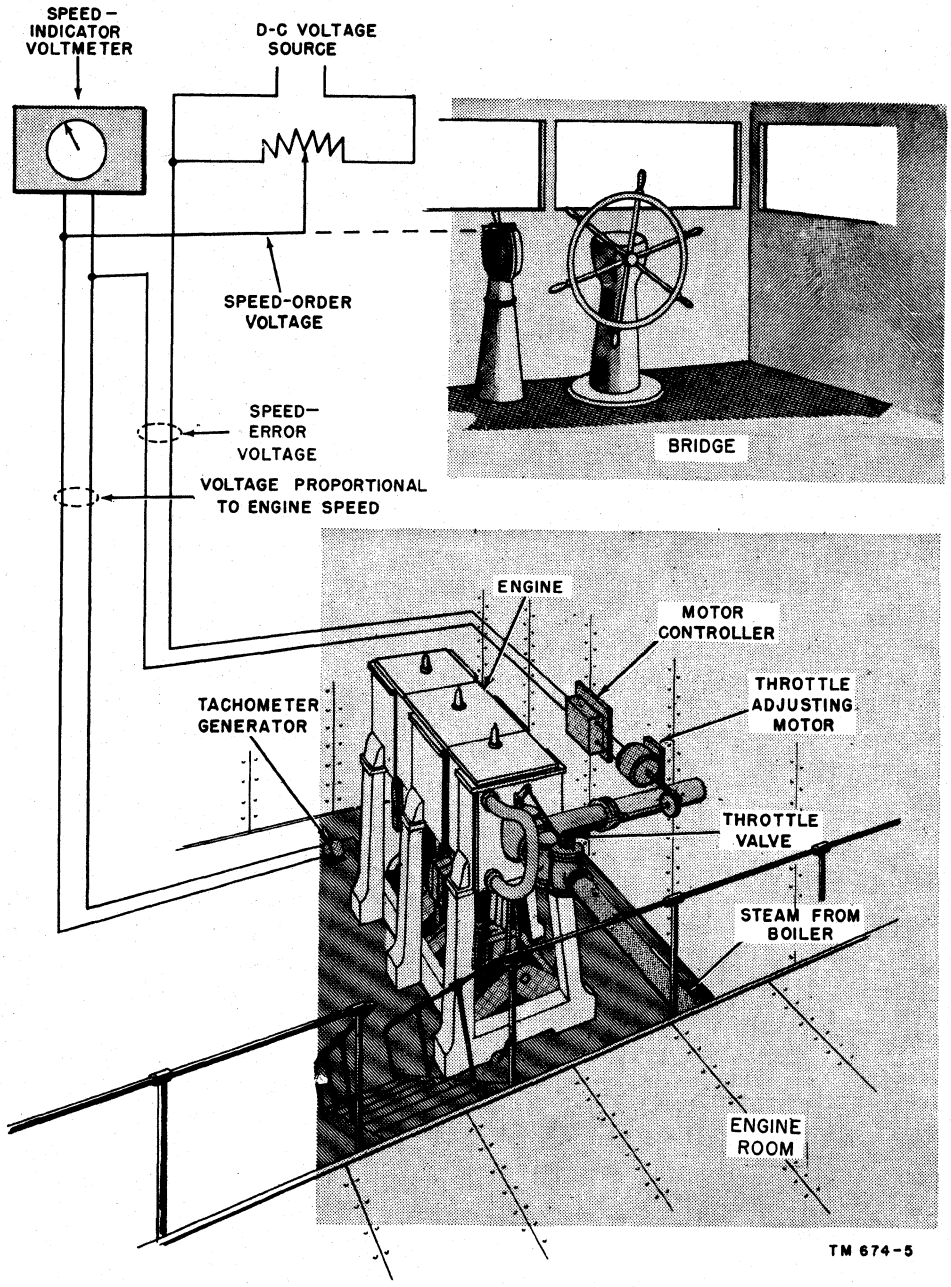


Figure 5. Automatic servo loop.

by the sensing element, also on the bridge, and compared with the speed order which originated on the bridge. The resulting speed-error signal is sent back to the engine room where it actuates the throttle adjuster. The throttle adjuster, incidentally, is an example of an open control system that is part of a closed system, in that it follows the order it receives from the sensing element and pays no attention to anything else. The complete speed control system, however, is a closed one since it acts in response to a difference between actual engine speed and ordered speed.

c. Remote Control System With Data Transmission and Servo Follower. The system described above can be simplified slightly by putting the sensing element in the engine room. In the former case, the speed signal from the tachometer was sent from the engine room to the bridge and the speed-error signal was sent back to the engine room. In this case (fig. 6), only the speed order is sent from one location to the other by way of the data-transmission system. This is an example of a closed control system that is part of a larger open system. The equipment in the engine room is a closed system, since it compares the speed order with the actual speed and acts to reduce the error. When the system as a whole is considered, it is an open system, since the speed order sent down from the bridge is the actuating signal for the complete system, and this is not affected by any error in engine speed.

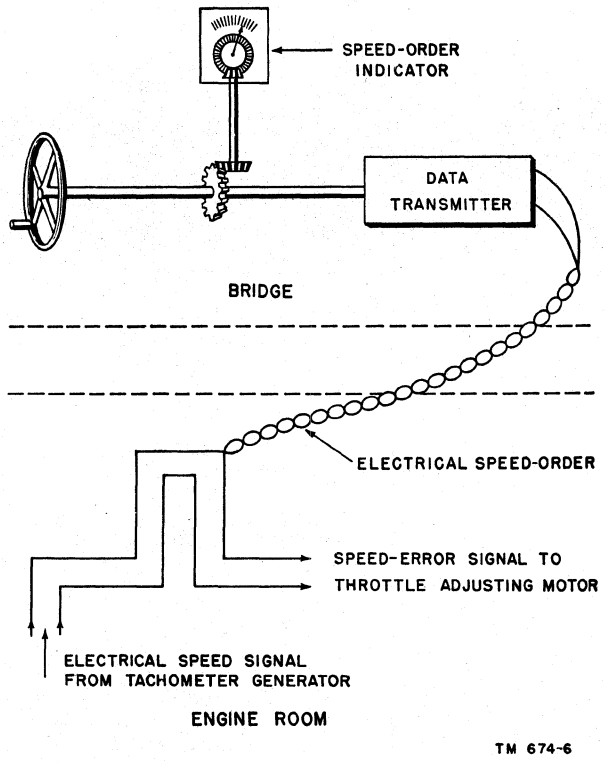


Figure 6. Data transmission and servo follower.

Section III. REPRESENTATIVE MILITARY APPLICATIONS OF SERVOS

8. Positioning Loads

Servos are used to position guns, searchlights, radar antennas, compass repeaters, control surfaces of aircraft, and rudders of ships. In general, they are used when the load is too heavy for a man, when the load is so located that a direct mechanical connection to the operating station is undesirable or impossible, or when the signal originates in other equipment and automatic operation is desirable.

9. Automatic Tracking

Servos used for automatic tracking in radar operate in response to signals provided by the radar itself. Tracking is the process of following a moving target with some device that indicates the target direction. In optical tracking, a telescope is kept pointing at the target by an operator (or sometimes by two operators who operate a pair of telescopes that are mechanically connected). The operator looks at the target through the telescope and moves the telescope to hold the target in the center of the field of view. In radar tracking, the radar is held pointing at the target. Sometimes this is done by operators who observe the radar output, but in automatic tracking it is accomplished by servo systems. The radar signals indicate any difference (error) between the actual position of the radar antenna and the desired position, that of pointing toward the target. An automatic tracking system is fast and precise. It generally is more accurate than a manual tracking system employing human operators, except in the presence of jamming. The enemy may jam a tracking radar in order to spoil the accuracy of its tracking. This also will spoil the accuracy of any gun-fire based on information from the radar. Jamming is accomplished by sending strong signals at the operating frequency of the radar.

These are picked up by the radar receiver and cause it to deliver output signals that have nothing to do with the tracking error. If the jamming signals are strong enough, they may mask the tracking-error signals almost completely and make the radar inoperative. With jamming, the servo tracking system fails, because servos are not designed to exercise judgment and are consequently unable to distinguish between the real error signals and the false ones that result from jamming. Special servos can be built, however, that are useful in combatting certain types of jamming, and these perform better than human operators under the conditions for which they are designed. Chapter 4 describes in detail several examples of servo systems and component applications. These examples are simplifications embodying principles used in actual military equipment.

10. Summary and Review Questions

a. Summary.

(1) The effectiveness of modern military equipment often depends on the precision with which shafts can be set. In antiaircraft predictors, for example, the continuous flow of radar information is reproduced in the shaft settings of a predictor, which utilizes this information to compute a future target position and gun-pointing orders.

(2) *Servo systems* and *data-transmission systems* allow the setting of one or more shafts to be repeated automatically at a number of other shafts, which may be located great distances away.

(3) Control systems, generally, are used to accomplish certain tasks more easily, more rapidly, or more precisely than human operators. They may be divided into two types—open and closed. An open system operates only in response to external orders; a closed system bases its action both on external orders and on the behavior of the load that it controls.

(4) A servo system is usually a closed control system; that is, the behavior of the controlled quantity as well as the external order causes the controller to act. A servo loop can be compared to a system by which the speed of an engine is regulated. For example, the engine drives a tachometer. A sensing element compares the actual speed registered by the tachometer with a speed order received from an external source, and develops an error signal that is the difference between ordered speed and actual speed. This controls a throttle adjuster which varies the speed of the engine.

(5) Servo systems have many applications, such as positioning guns and searchlights, automatically altering the pitch of aircraft propellers, and in automatic-tracking radar and antiaircraft predictors.

b. Review Questions.

(1) What is the general purpose of a servo system?

(2) Define an open control system; a closed control system.

(3) What is a servo loop?

(4) Cite four servo-system applications.

(5) What is jamming?

(6) What is repeat-back?

CHAPTER 2

BASIC SERVO PRINCIPLES

Section I. ELEMENTARY POSITIONING SERVO

11. Introduction

Certain basic principles govern the operation of any servo. These are presented in this chapter by considering elementary servos of two types, analyzing their behavior, and showing how their performance is improved by various modifications. The components of the servos (motors, amplifiers, generators, and so on) are described only in terms of the tasks they accomplish. A detailed discussion of these various servo components appears in chapter 3. The first of the two elementary servos to be considered is a positioning servo, chosen both for its simplicity and because it is representative of a large class of servos used in military applications. The 16-inch guns of a battleship, for instance, are moved by positioning servos; and in contrast, the dials of the compass repeater described in paragraphs 107 and 108 also are set by a positioning servo. This type of servo consists of a load whose position is controlled in accordance with an external position order and an actuator that moves the load. The actuator operates in response to the difference between the actual load position and the position called for by the external order.

12. Servo Elements

The various elements shown in figure 7 are present in any positioning servo, although, in many cases, a single component serves as more than one element. A synchro control transformer, for example, is a combination data receiver, follow-up, and sensing element. It is described in detail in paragraph 72. The elements are discussed here only from the standpoint of their functions in a servo. The actuator, for instance, is assumed to be an electric motor, and the question of whether it should operate on a-c or d-c, or whether it should be replaced by a hydraulic device, is unimportant in analyzing the action of the servo as a whole. Discussion of the relative merits of different actuators is contained in paragraphs 45 through 51.

a. Load. The load is a heavy mass that is positioned by the servo in response to an external position order. Since the operation of the servo is strongly affected by friction, or by auxiliary elements that simulate the effect of friction, for this explanation the load is assumed to move without friction.

b. Actuator. This is the device that moves the load. In this discussion, it is assumed that the actuator is an electric motor. The type of motor is not important at this time, since it depends primarily on the size of the load, and the speed with which it must be moved.

c. Controller. This is the element that controls the operation of the actuator in response to an error signal it receives from the sensing element.

d. Follow-up. This is, in effect, a data-transmission system which repeats the actual load position to the sensing element. In figure 7, the end of the follow-up system is shown as a small disk called a follow-up head. This is connected to the load by shafts and gearing. Since the follow-up head is not called upon to exert any force, the mechanical linkage between it and the load may be extremely light. The other linkage, coupling the actuator to the load, is normally heavier. Its actual design depends on the power output of the actuator and this, in turn, depends on the size of the load and the speed with which it is to be moved.

e. Data-Transmission System. Although this is not properly a part of the servo, it is shown in figure 7 to make the example easier to understand. The external order is set into the system by adjustment of the small hand wheel and is carried by a shaft to the data receiver. The data-

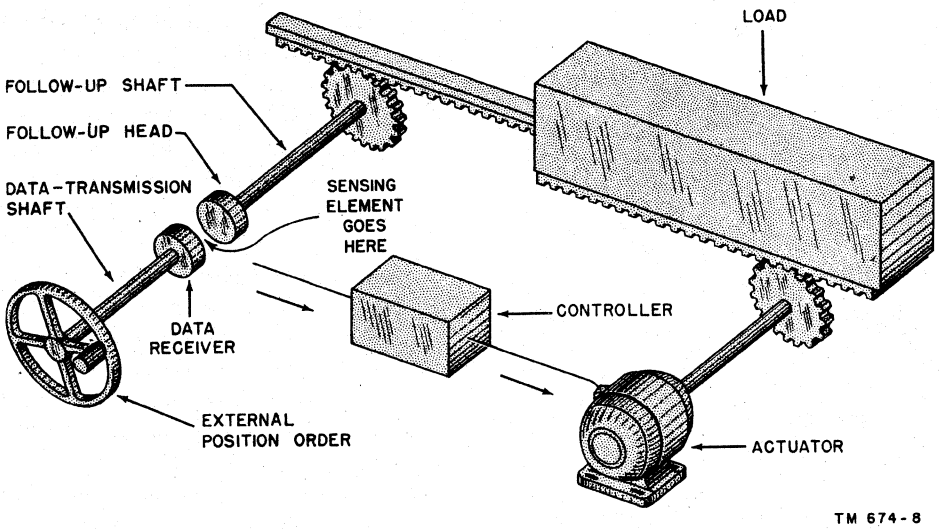


Figure 7. Positioning-servo elements.

transmission link is nothing more than a length of shaft.

f. Data Receiver. The data receiver is shown as a small disk on the end of the data input shaft. Its function is to repeat the external order to the sensing element.

g. Sensing Element. This is not shown in figure 7, since a number of different sensing elements are discussed later. The function of the sensing element is to receive the external position order from the data receiver, and the actual load position from the follow-up head, compare these, and originate an error signal, electrical in this case, that depends on the position error.

13. Signal From Sensing Element

The signal from the sensing element depends on the error, which is the difference between the actual load position and the position called for by the external order. In this case, the error signal is electrical, but it can be of other types, such as mechanical or hydraulic. Similarly, the inputs need not be mechanical. In the automatic engine-speed control system described in paragraph 7*b*, both the speed order and the speed information are in the form of voltages, and the sensing element is a voltage-subtraction circuit, the output of which is the difference between the input voltages.

14. Control Methods

The behavior of the servo depends on the way in which the actuator responds to an error in the position of the load. In turn, this response depends on the signal originated by the sensing element and sent to the controller. The method of control, or the way the actuator is directed to respond to an error, depends on the sensing element and on various auxiliary devises that may be introduced ahead of the sensing element. There are three representative methods of control—on-off control, stepwise control, and proportional control—and these terms are frequently used to describe servos. For example, an on-off servo is one that uses on-off control.

a. On-Off Control. On-off control (fig. 8) usually is provided by a contact-type sensing element. The mechanism shown is called also, on occasion, a contact follow-up head, or simply a contact follow-up. Two contact springs are carried on the data-receiver head, and a single contact arm is carried on the follow-up head. When there is no position error, the contact arm lies midway between the two contact springs and no signal is sent to the controller, since there is no contact between the springs and the arm. When there is an error, the contact arm will touch one or the other of the two springs and close a circuit, causing the actuator to drive the load in the proper direction. The contact arm is made flexible so that the mechanism will not be damaged by a large error. The contacts may carry the full motor current, and it is then unnecessary to use a controller. If this is undesirable, the signal from the contacts may be used to actuate one of a pair of relays which carry the motor current, and the controller is therefore the two relays. In any case,

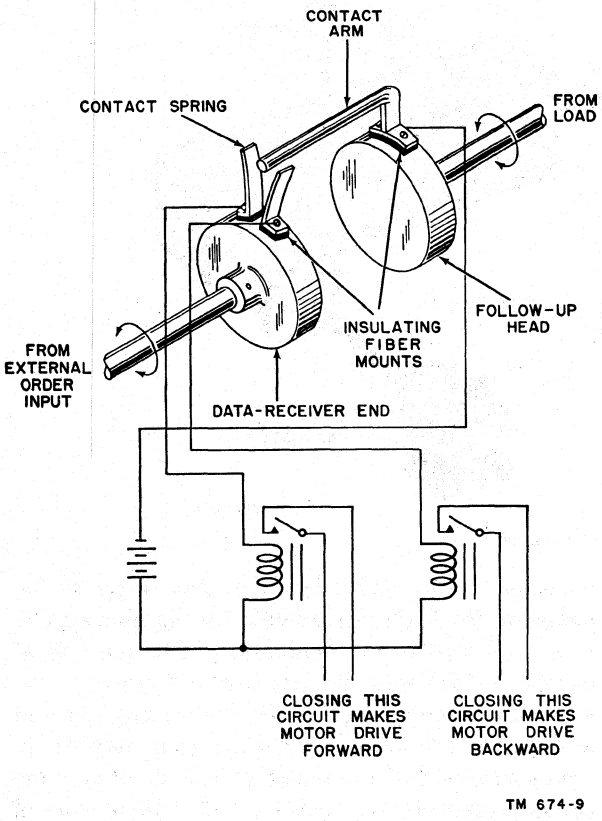


Figure 8. On-off control mechanism.

the motor is either off or full on (in one direction or the other), and the method is called on-off control.

b. Stepwise Control. In a stepwise servo, any error is corrected in a series of steps, the amount of correction in each step being proportional to the error that exists at the start of the step. The servo, therefore, operates in cycles. During the first part of each cycle, some device notes the error; during the second part of that cycle, the actuator makes a correcting step that is proportional to the error. A mechanism that will provide stepwise control is shown in figure 9. This mechanism is added to the system before the sensing element between the follow-up shaft and the follow-up head. In this case, the sensing element is assumed to be the simple on-off element described above. The follow-up head is connected to the follow-up shaft by two driving systems. The main drive is connected directly by means of a flexible shaft. The auxiliary drive is by way of gearing, rigid shafts, and a clutch. The main drive, since it is a direct connection, attempts to make the follow-up head move with the follow-up shaft. While the clutch is disengaged, the auxiliary drive does nothing; however, when the clutch is engaged, it turns the follow-up head in the same direction as the follow-up shaft but, because of the gearing, turns it faster. With a gear ratio of 2:1, the follow-up head will be turned 10° by the auxiliary drive (when the clutch is engaged) when the follow-up shaft has turned 5°. During the first part of the operating cycle, the controller is disabled and the clutch in the auxiliary drive is disengaged. The follow-up head, therefore, assumes a position that matches that of the follow-up shaft, and the contacts of the sensing element see the actual error. During the second part of the cycle, the clutch is engaged and the controller is allowed to operate. The actuator then moves the load in the direction that reduces the error. Because of the auxiliary drive, the follow-up head is turned toward zero error position faster than the load moves to its proper position. At some point short of complete correction, the sensing element then will see a zero error and will turn the actuator off. At the same time, an extra circuit, controlled by the contacts of the sensing element, disables the controller and disengages the clutch in the auxiliary drive, thus starting the first part of the stepping cycle again. After a short interval, during which the flexible shaft of the main drive untwists itself and brings the follow-up head back to coincidence with the follow-up shaft, the controller is energized once more and the clutch is engaged again to start the second part of the cycle. The error thus is corrected in the stepwise way described above. If the gear ratio in the auxiliary drive is 2:1, the error will be halved in each step. Other mechanisms may be devised which will control the step length by altering the duration of the step instead of directly controlling its length, or by changing the speed at which the actuator moves the load. All, however, result in the stepwise correction from which the method receives its name.

c. Proportional Control. The proportional control system is the one most generally used. Reasons for its preference in most applications are discussed in paragraph 37. The simplest way of achieving proportional control is to replace the contact-type sensing element with a potentiometer (fig. 10). The body of the potentiometer is carried on the data-receiver head, and the slider is

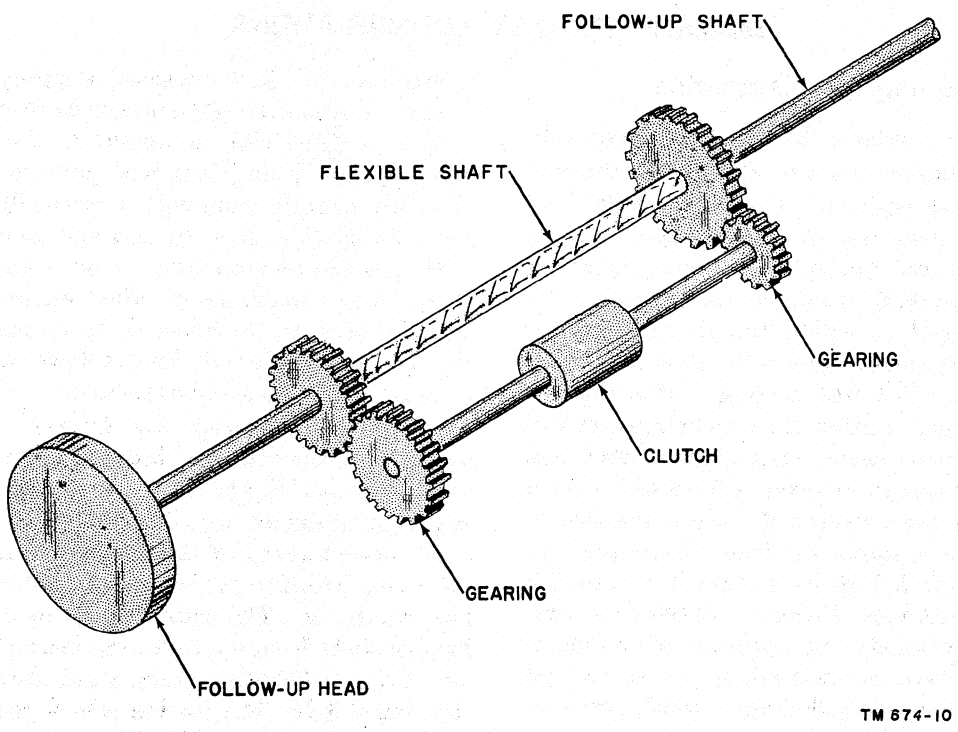


Figure 9. Stepwise-control mechanism.

driven by the follow-up head (although the positions may be reversed). The potentiometer is excited by a balanced input; voltages of opposite polarity are applied to the two ends if it is in a d-c system, or of opposite phase in the case of an a-c system. When the slider is at the center of its range, it will deliver an output of 0 volt. The potentiometer and slider are so mounted on the two heads that this output is 0 volt when the load is at its proper position. When an error exists, the slider is displaced from the center of its range by an amount that is proportional to the error. The error signal is, therefore, a voltage proportional to the error, and with the usual controllers and actuators, the force—in the case of small errors—exerted by the actuator is proportional to the error. Although it is possible to omit the controller or replace it with a pair of relays in the on-off and stepwise methods, this cannot be done here unless the potentiometer is to carry the full motor current. The usual method is to use the potentiometer output as the input signal for an amplifier of some sort, and let this provide the power for the motor.

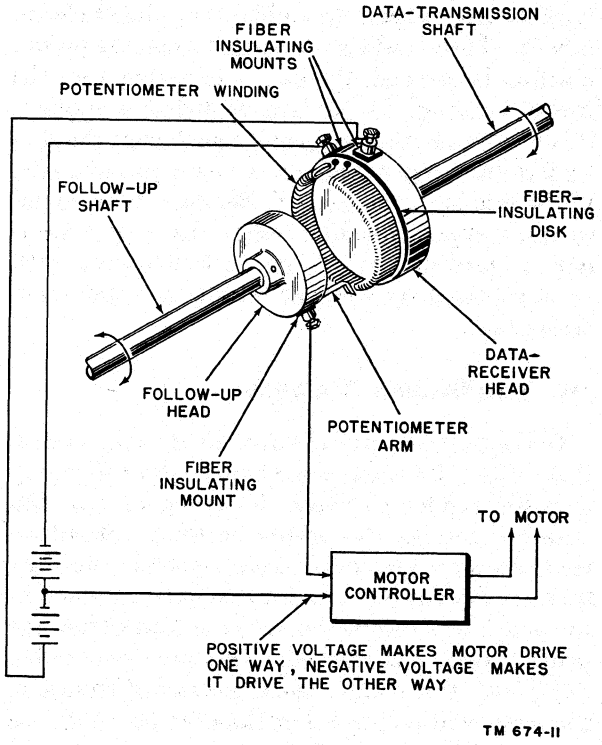


Figure 10. Proportional-control sensing element.

Section II. STABILITY CONSIDERATIONS

15. Overshooting and Oscillation

In the three systems described in paragraphs 11–14, the actuator exerts no force when the load is in its proper position. Therefore, if the load is brought to rest at a position of zero error, it will remain there. If the load is not at its proper position (because, for example, the position order has been changed), it will be brought to the proper position but its momentum will cause it to coast past. This is called overshooting. After the load passes its proper position, the sensing element will detect an error opposite to the original error, and will cause the actuator to exert a force which slows the load and then returns it toward the proper position. The distance the load travels past the proper position before its motion is reversed is called the *overshoot distance*. Successive overshooting, alternately, in opposite directions is called *oscillation*, or *hunting*, and a servo that oscillates or hunts is called an *unstable servo*, or one that has instability. As an example, let us consider the behavior of a ship with an inexpert helmsman as part of the steering servo. If the ship is off its proper heading, rudder is applied to bring it back. If the rudder is centered when the proper heading is reached, the ship will swing past the proper heading. Opposite rudder then is applied; this first checks the swing and then brings the ship back to the proper heading, which it passes again. If the steersman does not understand that he has to apply opposite rudder before the proper heading is reached, this can go on indefinitely until he is replaced by someone who is a better servo component.

16. Stabilization Methods

In the example given above, the steering system is stabilized by using a steersman who will apply opposite rudder to check the swing of the ship before it reaches the proper heading. Stabilization of a servo system is accomplished in the same way. A mechanism is added that causes the actuator to apply a reverse force to the load before the proper position is reached. This process is called *damping*. With only a small amount of damping, the servo will oscillate, but the overshoots will be successively smaller and the oscillation finally will die out. A servo in which the load comes to rest after one or more overshoots is called an underdamped servo. With increased damping, the load is slowed more strongly and comes to rest at the proper position with no overshoot. The smallest amount of damping that will prevent overshoot is called critical damping; a critically damped servo reduces the error to zero and holds it there in the shortest possible time. A servo having more than critical damping is called an overdamped servo; it takes an unnecessarily long time to reduce the error to zero since the load is slowed down more than is required to avoid overshoot.

a. Viscous Damping for On-Off Servo. A mechanism that will provide damping for an on-off servo is shown in figure 11. It is similar to the step-control device described earlier in that it is incorporated ahead of the sensing element in the follow-up linkage. As before, the follow-up head has two drives. The main drive is by means of a flexible shaft from the follow-up shaft; the auxiliary drive is through gears, rigid shafts, and a slipping clutch. The gearing is so chosen that the auxiliary drive moves the follow-up head faster than the follow-up shaft (except, of course, when the clutch slips), whereas the main drive attempts to turn the follow-up head precisely with the follow-up shaft. The slipping clutch consists of two paddle wheels running in a chamber filled with oil. One paddle wheel is connected to the driving shaft of the clutch, the other to the driven shaft. When one paddle wheel is turned, it whirls the oil in the chamber, and this tends to drag the other wheel around in the same direction. The strength with which the second wheel is dragged depends on the difference in speed between the wheels. Suppose, now, that the load is at rest but not in the proper position, a condition that can occur if the position order is changed suddenly. Since the load is at rest, the slipping clutch transmits no force, and the flexible shaft is not twisted. The follow-up head is, therefore, in its normal position as though the mechanism were not present, and the sensing element sees the error and turns the actuator on. The main drive attempts to turn the follow-up head at the same speed as the follow-up shaft. The auxiliary drive, however, tries to turn the follow-up head faster and succeeds in doing this until the resistance of the twisted flexible shaft is sufficient to balance the force transmitted by the slipping clutch. The follow-up head, is therefore, shifted

away from its normal position whenever the follow-up shaft is moving. The direction of shift is in the direction of the motion, and the amount of shift is proportional to the speed with which the follow-up shaft turns. The load then moves toward its proper position, and the follow-up head moves toward a position of zero error, but it moves ahead of the load. Shortly before the load reaches its proper position, the sensing element sees a zero error and turns the actuator off. Immediately after this, it sees an error of the opposite sign and reverses the actuator. This slows the load. If the system is correctly adjusted, the load will come to rest at exactly the proper position. At the same time, since the follow-up shaft slows and finally stops, the shift in the position of the follow-up head is reduced to zero so that it reaches its normal position, and the sensing element sees a zero error as the load comes to rest. The effect of the mechanism is to make an increasing error look larger and a decreasing error look smaller, or even like an error in the opposite direction. A somewhat similar damping effect could be obtained by running the load and its driving mechanism in a bath of heavy or viscous oil. This would exert a drag on the load that would tend to oppose its motion with a force proportional to the load speed. Because of this similarity, damping that depends on load speed alone is known as viscous damping.

b. Viscous Damping for Stepwise Servo. The same mechanism may be used to provide viscous damping for a stepwise servo. If it is inserted in the follow-up linkage before the other mechanism that provides the stepping action, it will provide a modified error signal to the stepping device, and the lengths of the steps will be proportional to the modified error. As the load moves toward its proper position, the indicated error will be smaller than the actual error, and consequently the steps taken by the servo will be smaller with the damping mechanism than without it. Finally, when a point is reached at which the indicated error has changed its sign, the actuator will be reversed. If the mechanism is adjusted correctly, this will be the last step and the actuator will be turned off just as the load comes to rest at the proper position.

c. Viscous Damping for Proportional Servo. Viscous damping can be obtained for a proportional servo in the same way as for the other servos, by the insertion of the viscous damping mechanism just described. A much simpler way, however, is to develop the damping signal electrically and add it to the output of the potenti-

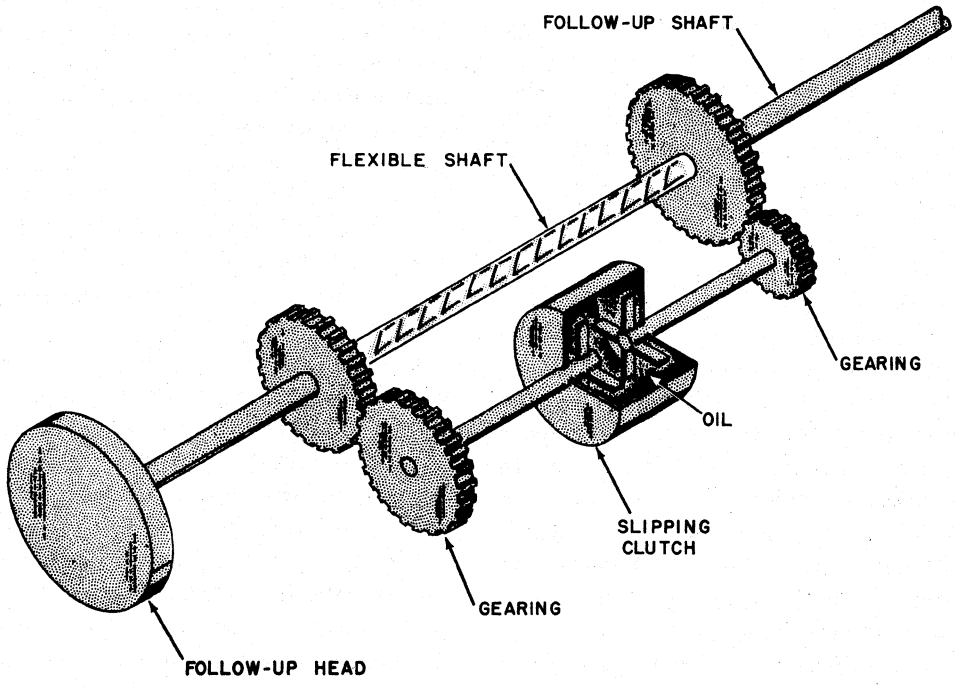


Figure 11. Viscous-damping mechanism.

ometer. This is done by means of a tachometer generator, which is a generator having an output voltage proportional to its speed. Adding the output voltage of the generator to that of the potentiometer has the same effect as displacing the potentiometer slider. If the polarity is correct, the effect will be precisely the same as that of the viscous-damping mechanism. The direction of the displacement, or the voltage shift which is equivalent to a displacement, depends on the direction in which the load is moving. The amount of the displacement is proportional to the speed at which the load moves.

17. Effect of Overdamping

In either an on-off or a stepwise servo, the effect of overdamping is to cause reversal of the actuator earlier than is necessary to avoid overshooting or hunting. In a proportional servo, the effect is one of excessive damping force. In any of the servos, the load takes longer than necessary to reach its proper position. In general, overdamping is undesirable and should be avoided. Many servo systems have what are called *anti-hunt controls*. These controls adjust the amount of damping, and should not be set past the point of critical damping where oscillation ceases.

Section III. ERROR CONSIDERATIONS

18. Dead Space

When a load controlled by a servo is at rest in a position other than the one called for by the external position order, the sensing element normally recognizes the existence of an error, and the resulting error signal that it originates causes the actuator to move the load toward its proper position. However, a contact type sensing element does not recognize the existence of an error unless it is large enough to cause the contacts to close. Similarly, in a proportional servo, the error signal resulting from a very small error may not be large enough to enable the actuator to overcome the starting-friction forces in the drive mechanism. In either case, the positioning servo will act only in response to errors that exceed some minimum value. If, for example, the load can be displaced .02 inch in either direction from its proper position before the servo acts, the servo is said to have a dead space of .04 inch. Whenever the load is in the dead space—the region extending from a point .02 inch on one side of the proper position to another point .02 inch on the other side—the servo takes no action. Dead space results in inaccurate positioning of the load. Although dead space cannot be eliminated completely, it is desirable to reduce it to a minimum value. This is done for an on-off servo by the introduction of *dither*—which is explained below—for a stepwise servo by a reduction in step size, and for a proportional servo by an increase in the error signal.

a. Jitter in On-Off Servo. Dead space in an on-off servo is the result of spacing between the forward and reverse contacts of the sensing element. An obvious method of reducing dead space is to reduce the spacing between the contacts. Unfortunately, there is a limit to the reduction that can be achieved in this way, and when the spacing is reduced to a certain point, the following action will take place. Suppose the load is displaced just enough to close one of the contacts. The actuator then will start the load moving and it will travel until the opposite contact is closed. If the damping is adjusted properly, closing the second contact will cause the actuator to bring the load to rest. However, if the contacts are spaced too closely, it is almost impossible to avoid having the load thrown back by the actuator so that the first contact is closed again, and the cycle is repeated indefinitely. This behavior—oscillation over a small region about as large as the dead space—is called *jitter*. The minimum obtainable contact spacing is fixed by the necessity of avoiding jitter, and this limits the reduction in dead space that can be obtained by reducing spacing between contacts.

b. Introduction of Dither. A further reduction can be achieved, however, by the introduction of dither. The moving contact of the sensing element is made to vibrate, usually by a magnetic driving system similar to that in a buzzer, at a frequency called the dither frequency (A of fig. 12). When the load is at its proper position, the moving contact vibrates between the two fixed contacts, making connection with first one and then the other. The sensing element then delivers forward and reverse error signals alternately, in short pulses. Since the duration of the forward pulse is the

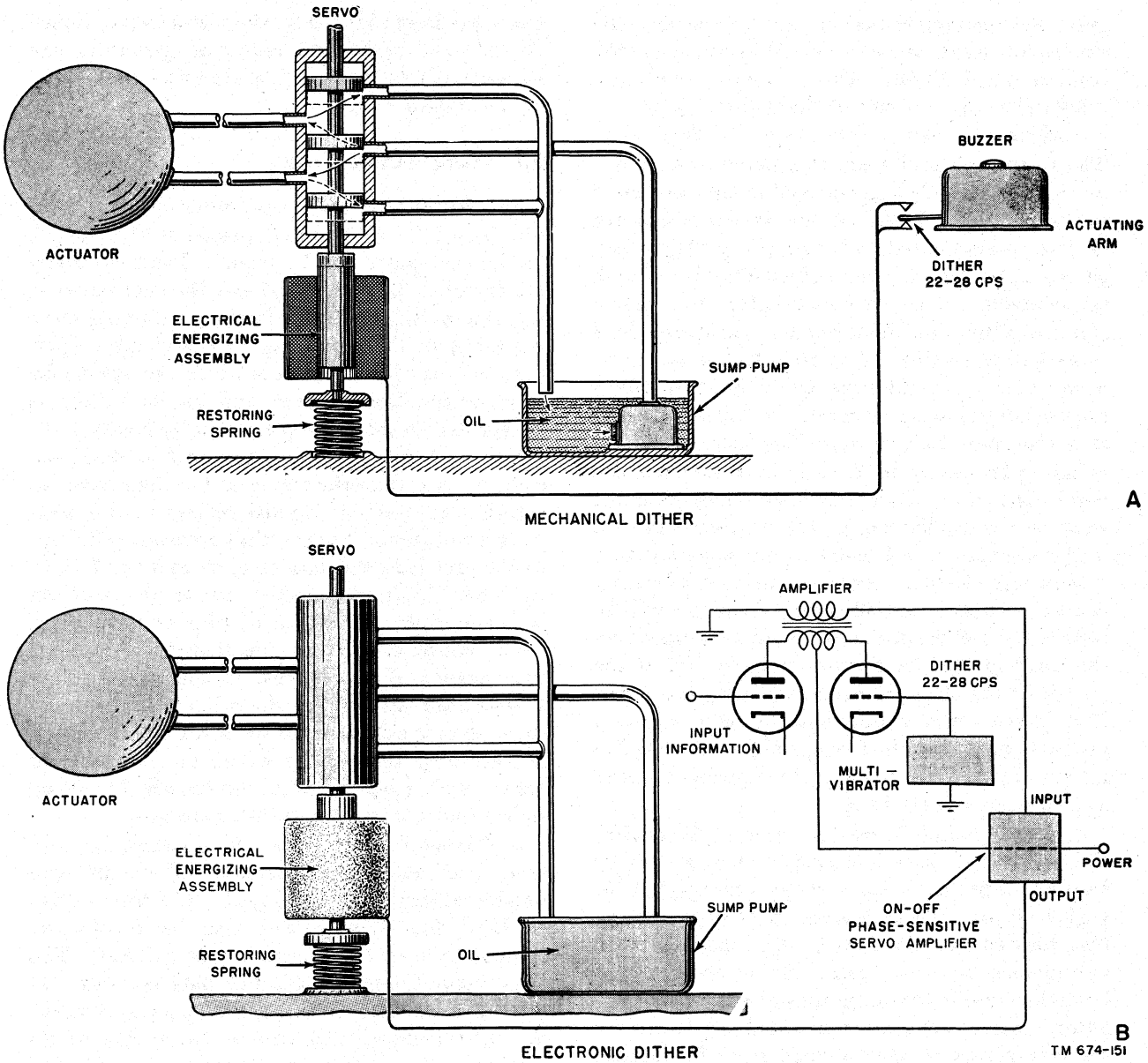


Figure 12. Dither application.

same as that of the reverse pulses, the actuator acts for equal time intervals in the forward and reverse direction, and the net effect is zero. However, for small errors that would result in no action without the dither system, the moving contact remains connected to one of the fixed contacts for a larger interval than to the other. The actuator then exerts force alternately in the forward and reverse directions, but acts in one direction for a slightly longer time than in the other, with a net result equivalent to gentle action in this direction. For large errors, the moving contact remains connected to one or the other of the fixed contacts, and the action of the servo is the same as that of one without a dither system. The effect of adding a dither system is to replace the dead space with a region in which the on-off servo acts like a proportional servo. The main objection to the use of dither is that it causes excessive wear on the actuator, and on the gearing that couples the actuator to the load. The electronic dither shown in B is a multivibrator and is applied to create an independently changing voltage to an amplifier, or any other type of modulator, as used in servo amplifiers. How-

ever, the characteristics of the mechanical and electronic dither can be combined to create an electromechanical dither. This is done by adding a relay in the plate circuit of the multivibrator.

c. Stepwise Servo—Reduction in Step Size. The amount of dead space in a stepwise servo can be reduced by reducing the contact spacing as in the on-off servo. Here, too, the reduction that can be obtained is limited by the necessity of avoiding jitter. If the step size for a given error is reduced, the contacts can be set closer before the system starts to jitter, and the minimum obtainable dead space will be smaller. Any reduction in step size, however, slows up the response of the servo unless the stepping rate is increased. If reduction in the step size and the corresponding increase in the stepping frequency is carried to an extreme, the resulting motion of the servo will cause as much wear on the mechanism as the introduction of a dither system. It is feasible to introduce a dither system into the stepwise servo, using a vibrating contact as with an on-off servo; the result will be replacement of the dead space with a region where the force exerted by the actuator, as well as the length of the steps, is proportional to the error. The system will not behave in the same way as a proportional servo, however, unless the stepping rate is so rapid that the actuator appears to exert a steady force on the load.

d. Proportional Servo—Increase in Error Signal. The dead space in a proportional servo may be reduced by providing a larger error signal for a given error. There is some limit to the reduction that can be obtained by this method, since any increase in error signal must be accompanied by an increase in the damping signal. Ordinarily, a proportional servo is not troubled by jitter, since the actuator exerts only a small force for a small error instead of its maximum available output, as is the case in on-off and stepwise servos without dither.

19. Effect of Noise on Dead Space

With the introduction of dither, an on-off servo becomes a proportional servo for small errors, and a stepwise servo acts in much the same manner. In both of these, and with the proportional servo as well, there remains a further limitation on dead space. Any electrical noise in the system will mask a small error signal and prevent the actuator from correcting the error. After the dead space has been reduced by the methods mentioned above, some additional reduction generally can be secured by lowering the electrical noise level of the system.

20. Instrumental Error

In addition to dead space, other errors usually are caused by the limited precision with which mechanical parts can be made. These normally are found in the follow-up head, the data receiver, and the sensing element. In the positioning servo described at the beginning of the chapter (par. 11), the position order is set into the system by rotating the data receiver, and the load position is repeated to the sensing element by rotating the follow-up head. To avoid having two load positions for a given orientation of the data receiver, rotation normally is limited to less than a complete revolution. Assume that rotation is limited to 300° for both the data receiver and the follow-up head. With reasonable care, these parts can be made with a precision of plus or minus ½°. This limit on precision means that it is impossible to guarantee that the error in the load position will be less than 1/600 of the full load travel when the system is satisfied and the error signal is zero. An error of this sort is called an instrumental error, and frequently is minimized by using coarse-fine systems and transfer circuits.

a. Coarse-Fine Systems. In a coarse-fine system, dual data input systems, follow-ups, and sensing elements are employed. The fine follow-up head, for example, may make 40 revolutions for one turn of the coarse follow-up head. The same ratio is used for the fine data receiver. If the servo operates from the fine sensing element, the instrumental error can be cut to $\frac{1}{40}$ of its original value. However, assuming that an error of 1° on the fine follow-up head is equivalent to an error of $\frac{1}{40}$° on the coarse system, a load movement causing 9° of motion on the coarse follow-up head results in a complete revolution of the fine follow-up head, and the fine sensing element notes a zero error. Thus it is possible to find a number of load positions for which the fine sensing element will see zero error, and these positions will be separated by distances corresponding to one revolution of the fine follow-up head. The physical construction of the fine sensing element must permit the follow-up head to rotate continuously past the fine data receiver

without damage. The coarse control element is therefore necessary, since there is only one load position for which both coarse and fine sensing elements see zero error.

b. Transfer Circuits. A transfer circuit (fig. 13) is used with a coarse-fine system in order to retain the precision of the fine system and the greater range of the coarse system. The load is positioned roughly by allowing the actuator to be controlled by the output of the coarse sensing element. When the coarse sensing element sees only a small error, control of the actuator is transferred to the fine sensing element and the load is positioned precisely. The transfer circuit is operated by the error signal from the coarse sensing element. When this error signal is large, the relay is energized and control of the system is handed to the coarse sensing element for approximate position. After the coarse error signal has been reduced to some lower level, the relay allows control to revert to the fine sensing element.

21. Velocity Lag

a. Definition. Suppose that the position order sent to a servo is changing uniformly. The load must move at constant speed in order to remain in the position called for. Under this condition, viscous damping produces an error called velocity lag. The effect of a viscous-damping device is to displace the follow-up head so that it runs ahead of the load when the load is moving. The mechanical device described earlier (par. 16*a*) actually does this, and the electrical damping method described in connection with the proportional servo (par. 16*c*) accomplishes the same effect by adding the generator signal to the output of the proportional sensing element. If the follow-up head runs ahead of the load, the load must run behind the follow-up head when it moves. The servo, by reducing the error signal to zero, makes the follow-up head move with the data receiver. The load, in lagging behind the follow-up head and the data receiver, also will lag behind the position order. The amount of the lag will be proportional to the velocity with which the load moves. The situation can be seen more clearly by considering a proportional servo with a potentiometer sensing element and a tachometer generator for damping. Whenever the load is moving, there will be an output from the generator. Since the servo reduces the total error signal to zero, the output of the potentiometer will be equal and opposite to that of the generator. There will be a position error proportional to the generator output and the velocity of the load, since the generator output is proportional to the load velocity. If friction is present, the velocity lag will be increased slightly, since the frictional forces are in the same direction as those produced by the actuator in response to the damping signal. Velocity lag is objectionable in any servo whose position order may change rapidly. It could be eliminated by removing the damping mechanism, but this would make the system unstable, which is even more undesirable. Two methods of elimination generally are used—compensation by addition of

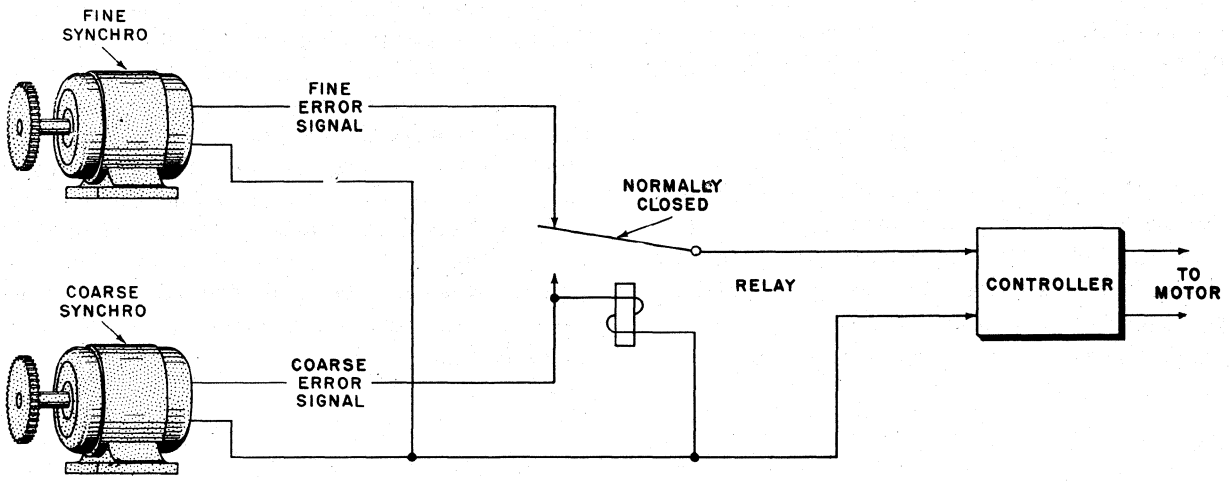


Figure 13. Transfer circuit.

order-rate signal, and error-rate damping (for a proportional servo).

b. Compensation by Addition of Order-Rate Signal. Since the load lags behind the position order by an amount proportional to the speed at which the load moves, one method of eliminating velocity lag is to provide a fictitious position order which is displaced from the real order. If the displacement is properly chosen, the load will lag behind the fictitious order by precisely the amount that allows it to follow the real order without error. This can be done by making the data-receiver head run ahead of the position order by an amount equal to that by which the follow-up head leads the load. A mechanism identical with the viscous-damping mechanism can be inserted between the data-transmission shaft and the data-receiver head to achieve the desired effect. Similar methods can be devised for cases in which the position order is not transmitted mechanically to the servo.

c. Error-Rate Damping. A better method of damping (than compensation by addition of order rate) is available for use with the proportional servo. This method is called *error-rate damping.* The complete error signal consists of two parts—one, proportional to the position error, is the signal that serves to position the load; the other, proportional to the velocity of the load, provides viscous damping and is responsible for the velocity lag. The damping signal is then proportional to the rate at which the load position changes, and velocity lag can be eliminated by subtracting a signal that is proportional to the rate at which the position order changes, the constant of proportionality being the same for both. The equation for this is—

$$E_s = K_1E + K_2R_1 - K_2R_2$$

where E_s is the complete error signal, K_1 and K_2 are the constants of proportionality, E is the position error, R_1 is the load position rate, and R_2 is the position order rate. The last two parts of the equation can be written as K_2 times the rate at which the load position changes minus the rate at which the position order changes: K_2 (R_1 minus R_2). The difference between the two position rates is equal to the rate at which the separation between the positions, load and ordered, changes. The last two parts then are equal to K_2 times the rate at which the difference between the load position and the position order changes. Since this difference is the position error, the equation can be written—

$$E_s = K_1E + K_2R_3$$

where R_3 is the rate at which the position error changes. A damping network is so designed that its output is equal to K_1, times the network input plus K_2 times the rate at which the input changes. The desired signal then appears as the output of the damping network when it has for an input the signal from the potentiometer. Error-rate damping is simpler than tachometer-generator damping, which it replaces, since the network has no moving parts. It provides damping and, at the same time, eliminates the velocity lag caused by the damping. It will not, however, eliminate other velocity lag such as that resulting from friction. Its name, error-rate damping, is derived from the fact that the complete signal consists of a part proportional to the error and another part proportional to the rate called error rate, at which the error changes.

22. Acceleration Lag

In addition to velocity lag, which may be eliminated easily in the case of a proportional servo, there is another error called *acceleration lag.* Suppose the position order changes nonuniformly. The ordered position then will move with changing velocity and the load must do the same. It requires force, however, to accelerate or decelerate the load in order to alter its velocity. The actuator is unable to exert any force unless the sensing element sees an error, and consequently the load will lag behind its ordered position when it is being accelerated and will run ahead of its ordered position when it is being decelerated. It is possible to compensate for acceleration lag, but this is rarely done.

23. Response to Step Input

The usual way of evaluating the performance of a servo is to consider the way in which it responds to certain standard input orders. One of these orders, called a *step input*, is a sudden displacement of the position order which leaves the load at rest in an incorrect position. The speed with which the resulting error is corrected is one measure of performance.

a. On-Off Servo Response. An on-off servo responds to a step input by accelerating the load smoothly until it reaches full speed, as shown in the curve in figure 14. The load then travels at a constant rate until it is slowed by the actuator in response to a reversal of the error signal. If the damping mechanism offsets the follow-up head by the proper amount, the reversal will occur at a point which will cause the load to be brought to rest at the proper position called for by the displaced position order.

b. Stepwise Servo Response. The response of a stepwise servo is the same as that of an on-off servo except that the load is accelerated in steps, moving at constant speed during the intervals between the steps, as shown by the curve in figure 15. When the load has once been brought to full speed, it continues to move at a constant rate between the steps unless frictional forces slow it down. The load is slowed by the actuator after the error signal reverses and, if the damping is properly adjusted, the load comes to rest in the desired position without overshoot.

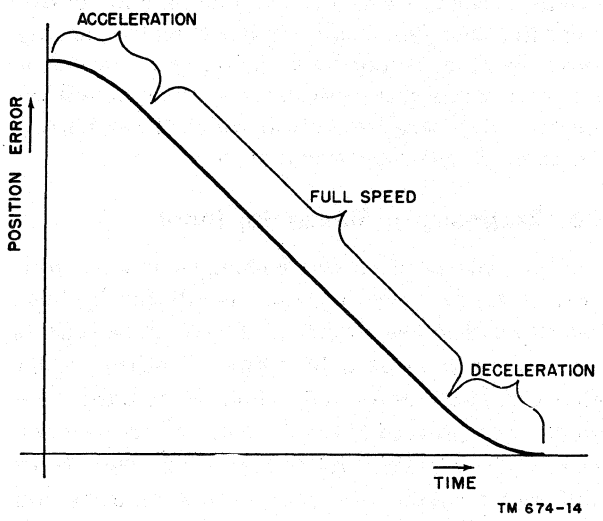


Figure 14. On-off servo response to step input.

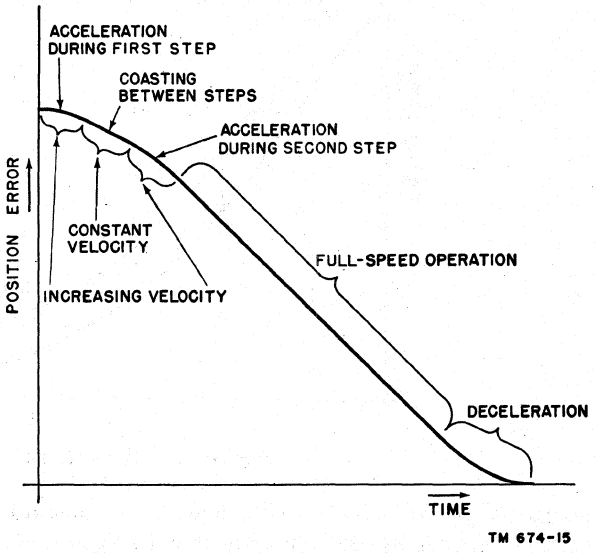


Figure 15. Stepwise servo response to step input.

c. Proportional Servo Response. If the displacement of the position order is small, a proportional servo responds, as shown in figure 16. The load first is accelerated to a speed where the error signal is matched by the damping signal. It then moves smoothly to its new position, decelerating as the error becomes smaller, since the actuator maintains the load speed at a point where the position error signal is balanced by the damping signal and the resulting error signal is zero. If the displacement of the position order is large, the resulting error signal may drive the controller to saturation, particularly if it is a vacuum-tube amplifier. In this case, the load is accelerated to full speed just as in the case of the on-off servo. It moves at constant speed thereafter until the error signal, which is the sum of the error and damping voltages, falls below the level required to saturate the controller. After this point, the load is slowed as described above. The constant-speed portion of the curve in figure 16 is present only if the controller is saturated.

24. Constant-Rate Input

Another standard input, called a *constant-rate input*, is obtained by changing the position order at a uniform rate. The ordered position then moves at constant speed and the servo drives the load at the same speed. There will be some velocity lag unless compensation has been introduced. A pro-

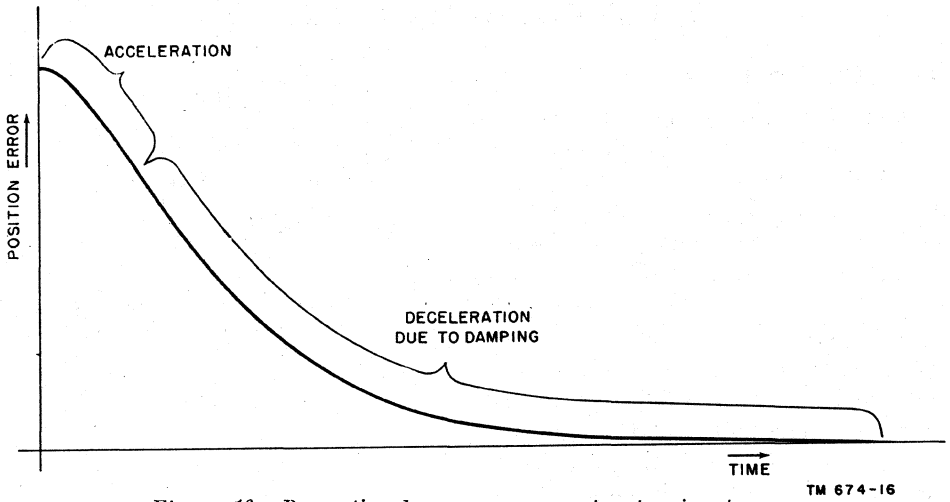


Figure 16. Proportional servo response to step input.

portional servo will drive its load at a constant rate, as shown by the straight line in figure 17. Either an on-off or a stepwise servo will act in the same way if it has been made proportional for small errors by the addition of a dither system. Without dither, servos of these types usually hunt, even though damping has been properly adjusted for matching the load position to a fixed position order without overshoot. The hunting results from the relatively large dead space. If the load speed drops slightly below the desired value, the servo does not act until the load has fallen sufficiently far behind the ordered position to close one of the contacts in the sensing element. The subsequent acceleration is not likely to be precisely what is required, so that the load then runs ahead of its proper position and causes the other contact to close.

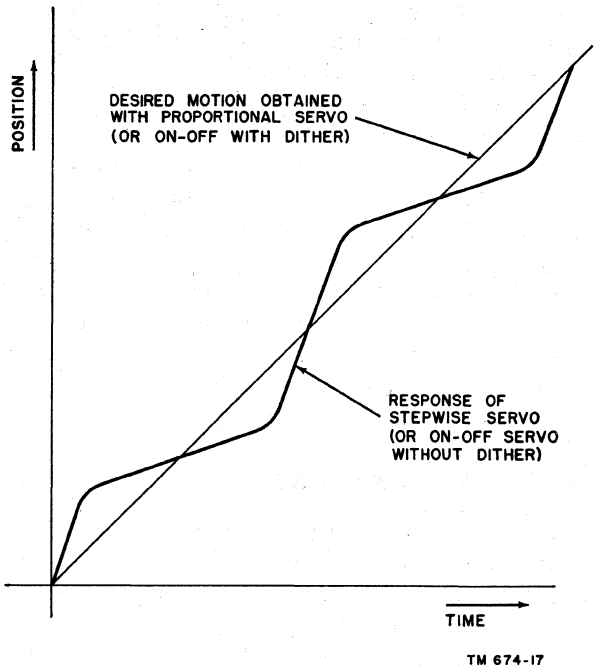


Figure 17. Response to Constant-speed input.

25. Slewing Rate

The maximum rate at which the actuator can move the load is called the *slewing rate*. This must be distinguished from the maximum following rate which, as its name implies, is the maximum rate at which the servo can cause the load to follow a changing position order. At the maximum following rate the actuating system still has some reserve that can be used to accelerate the load if this should become necessary. The maximum following rate, therefore, is always less than the slewing rate. With a proportional servo, or an on-off or stepwise servo with dither, the maximum following rate is the greatest rate at which the servo still operates in its proportional region.

26. Response to Sinusoidal Input

When the position order changes at a nonuniform rate, the servo response is affected by both velocity and acceleration lag. The combined effects usually are evaluated by using a position order that oscillates sinusoidally about some fixed position. The performance of the servo then is measured by its ability to follow input signals of different frequencies. Because both velocity and acceleration increase with increasing frequency of

the input signal oscillation, the lags increase and the performance of the servo becomes poorer as the frequency increases. Neither an on-off servo nor a stepwise servo can follow a signal of this type smoothly unless dither is introduced to obtain proportional action. An additional complication arises in the case of a stepwise servo, with or without dither, if the oscillation frequency of the input order is more than a small fraction of the stepping frequency. Generally, unless the duration of a stepping cycle is less than $\frac{1}{10}$ of an oscillation cycle of the input order, the error at the end of a step may be larger than that at the beginning of the step and the servo may actually drive the load in the wrong direction.

a. Response With Viscous Damping. In a proportional servo with viscous damping, or an on-off or stepwise servo with viscous damping and dither, the effect with sinusoidal input is primarily one of increasing lag. The load oscillates, following the position order, but with a lagging phase difference as shown by the curve in figure 18. There is little difference between the amplitude of the load oscillation and that of the position order oscillation until the frequency reaches a point at which the phase lag is 90°. This frequency is called the *natural frequency* of the servo. For frequencies higher than this, the amplitude of the load oscillation falls off rapidly. These frequencies are usually unimportant, however, because the error is sufficiently large to cause nonproportional operation and poor following.

b. Response With Velocity-Lag Compensation. The response to sinusoidal input is changed somewhat by the addition of compensation for velocity lag, whether this is obtained by actual compensation, or by the use of error-rate damping. The

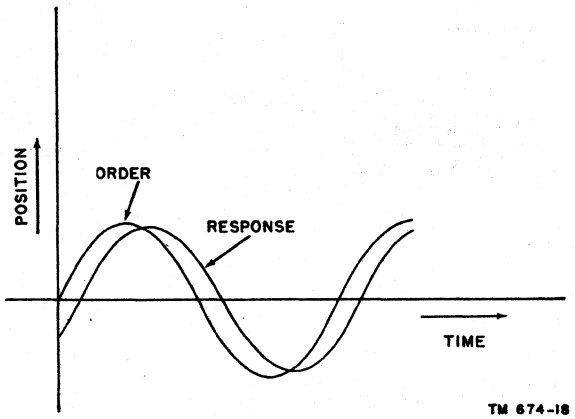


Figure 18. Response to sinusoidal input.

load follows the position order with only a small phase lag for frequencies up to the natural frequency of the servo—the frequency at which the viscous damped servo operates with a 90° phase lag. Above this point the phase lag rapidly increases and amplitude of response falls off. The amplitude of the load oscillation is the same as that of the position order oscillation at low frequencies, and is slightly greater at high frequencies. This is the result of velocity lag compensation, which makes the effective position order run ahead of the actual position order. Beyond the natural frequency, the response of the error-rate damped servo falls off in amplitude. One of the merits of error-rate damping, or viscous damping with velocity-lag compensation, is a marked increase in the frequency range of the compensation servo over that of an uncompensated servo, thus allowing the compensated servo to follow oscillating position orders over a greater frequency range.

Section V. (SIMPLE) RATE SERVO

27. Servo Operation

A rate servo is one that controls the rate, or speed, of a load instead of controlling the load position. It varies the rate at which the load moves in response to an external rate order. A typical example of rate servo is found in radar antenna systems where a rheostat is used to vary the field voltage, which decreases or increases the speed of the motor. Thus the antenna is turned at a faster or slower rate.

28. Servo Elements

In the rate servo illustrated in figure 19, the load is a flywheel, which turns at a controlled rate. The actuator is an electric motor, and the controller is an amplifier. The follow-up is a tachometer generator developing an output proportional to its speed. The data-transmission link is a wire over which the speed order is sent in the form of a voltage. There is no separate data receiver, and the sensing element is a simple voltage-sub-

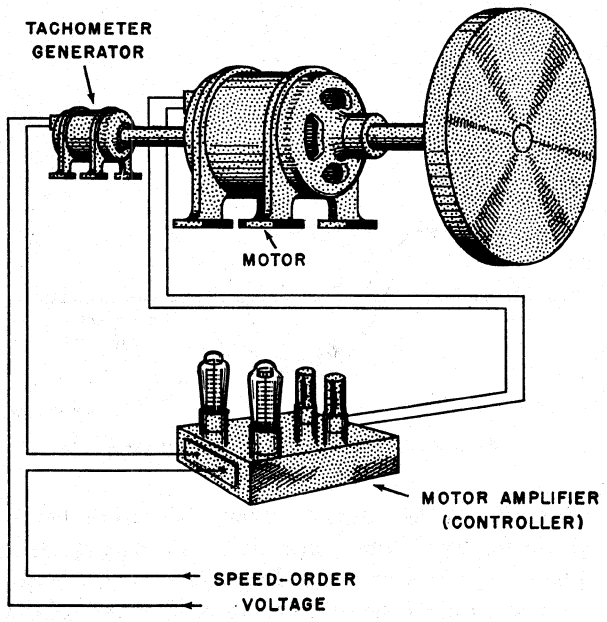


Figure 19. Rate servo.

traction circuit in which the speed order and the tachometer output are compared.

29. Signal from Sensing Element

The signal from the sensing element is the voltage difference between the speed order and the tachometer-output voltages. The signal is proportional to the speed error, and is sent to the controller, where it causes the actuator to increase or decrease the load speed.

30. Control Methods

On-off control can be accomplished by allowing the speed-error signal to close one relay when the speed is too high and another relay when the speed is too low. Because of the large dead space, the load speed will fluctuate between two values, one of which is higher than the speed order, and the other lower. Stepwise control is difficult to achieve except in cases where a stepwise servo is used to adjust the speed of the motor driving the flywheel. The use of an auxiliary servo for this purpose is similar to the use of an auxiliary throttle adjuster in the engine speed-control system described in paragraph 5. In practice, the rate servo usually is operated with proportional control. It runs at a speed slightly below the speed order, the resulting error being just sufficient to develop an error signal that will cause the motor output to balance the frictional forces in the system.

31. Braking for Speed Control

It is feasible to use the error signal to control a brake. The braking force is increased when the speed is too high and decreased when the speed is too low. This method wastes power and does not allow operation in both directions unless there is some provision to reverse the motor when the sign of the speed order is changed. However, many phonograph motors use this method.

32. Stability Considerations

The rate servo has no difficulty equivalent to the coasting of a positioning servo, and there is no tendency for the speed to continue changing after the actuator has been cut off. For this reason, the rate servo is inherently stable. Because of the large dead-space characteristic of on-off control without dither, a condition equivalent to jitter will be present if that type of control is used; however, a rate servo generally uses proportional control and has no stability problems.

33. Maximum Rate

There is a maximum rate at which the motor will drive the load. However, maximum rate usually is understood to mean the maximum *controlled* rate at which the load can be driven. This is the maximum rate at which the motor and controller are operating in the proportional region.

34. Acceleration Error

When the speed order changes, the load is accelerated or decelerated to the new speed. There must be a speed error while this is happening, because the actuator will not exert the required force on the load except when a speed error is present. It is possible to compensate for this by means of a circuit that makes an increasing speed order seem larger and a decreasing speed order seem smaller. Such a circuit, although it is electrical, behaves in the same way as the viscous-damping mechanism and the velocity-lag compensator. In practice, the acceleration error is small, and compensation is not usually necessary.

Section VI. RELATIVE MERITS OF DIFFERENT CONTROL METHODS

35. On-off Control

The on-off servo used without dither is simple and inexpensive. It is not precise because of the large dead space imposed by the necessity of avoiding jitter. The on-off servo without dither behaves poorly in following a rapidly changing order or one whose rate of change is nonuniform. It is used normally for approximate control with external orders that are more or less constant. Its performance is improved with the addition of dither, but when the system involves mechanical linkages, dither is undesirable because of the increased wear it produces.

36. Stepwise Control

The stepwise servo is more complicated than the on-off servo, but its performance is better. It frequently is used in place of the on-off servo when greater accuracy is required. Its performance is poor, however, with external orders that are changed rapidly.

37. Proportional Control

The proportional servo is more complicated than either the on-off or the stepwise servo. However, dead space can be eliminated substantially without the necessity of introducing dither, and velocity lag can be eliminated through the use of error-rate damping instead of viscous damping. Because of these advantages, the proportional servo is the type generally used in military applications. For this reason, the discussion in paragraphs 38 through 44 applies primarily to proportional servos.

Section VII. MODIFIED ERROR SIGNALS

38. Signal Proportional to Error

The signal sent to the controller of a proportional servo may be thought of as the sum of two or more separate signals. The most important of these signals is the one that is proportional to the error. In a positioning servo, this signal is proportional to the difference between the actual load position and the ordered position. In a rate servo, it is proportional to the difference between the actual speed of the load and the desired speed. The signal proportional to the error is the essential control signal, since it informs the controller of any difference between the ordered and actual values of the controlled quantity.

39. First Derivative of Error

In some servo systems, the controlled quantity has a tendency to continue changing for a short time after the actuator has been turned off. In general, a positioning servo is subject to this tendency and a rate servo is not. Where this tendency is absent, a servo is inherently stable and can be controlled by the simple error voltage discussed in paragraph 14*c*. The positioning servo, which always has this tendency, is inherently unstable and must be damped in order to avoid oscillation. A signal proportional to the first derivative of the error, which is the rate at which the error changes, may be used to obtain damping without introducing any velocity lag. This signal, also called an error-rate signal, is the stabilizing signal for the servo.

40. Second Derivative of Error

A signal proportional to the second derivative of the error is not used normally, but can be helpful when heavy damping is required. The first derivative of the error is the rate at which the error changes, and the second derivative of the error is the rate at which the first derivative changes. The first derivative provides damping by making an increasing error look larger and a decreasing error look smaller. The second derivative signal, when used, provides intensified damping by making an increasing error *rate* look larger and a decreasing error *rate* look smaller. Just as the first derivative signal allows the servo to anticipate the arrival of the load at its proper position in order to apply opposite force and bring the load to rest, so the second derivative signal allows the servo to anticipate the required slowing force and apply it in advance. This is useful when the mechanical parts of the servo are light and springy, so that the load not only coasts but continues to accelerate after the actuator is turned off. In such a servo, the load will not slow down at once when the actuator is reversed, and the earlier

application of the slowing force by use of the second derivative signal improves the response.

41. Integral of Error

The integral of a quantity over a time interval is the product of the average value of the quantity, during the time interval, by the length of the time interval. The integral of a large error which lasts a short time may be equal to the integral of a small error which lasts a long time. In particular, if the integral of the error over a period of time is zero, the average error over that period is zero. It frequently is desirable to make sure that the average error is zero and for this purpose a signal proportional to the integral of the error may be added to the control signal. If, for example, oil is delivered to a tank through a valve whose position is controlled by a servo, the addition of integral control will insure that, if the valve is not open wide enough for some period, there will be another period during which it will be open more than enough, so that the average valve position will be correct. Unfortunately, the addition of integral control makes the servo load try to coast past its ordered position in an attempt to compensate for the error which was present while it was approaching the position. This is unstabilizing, and the addition of derivative or error-rate control to damp the servo and make it stable once more will merely cancel the integral control effect. Fortunately, in applications where integral control is desirable, the existence of velocity lag is not normally objectionable. The servo then may be stabilized by viscous damping, which will not impair the integral control feature.

Section VIII. MECHANICAL PROBLEMS

42. Springy Coupling

Trouble usually arises from the use of light shafting or linkages in mechanical systems. These bend or twist under the forces exerted by the actuator, and the load does not respond immediately. More important, the load continues to accelerate for a time after the actuator is cut off. This trouble may be remedied by second derivative damping, which is the use of a signal proportional to the second derivative of the error. If acceleration lag is permissible, the response can be improved by adding the signal from an auxiliary follow-up that develops an output proportional to the load acceleration. If this is done, the stabilization method is called acceleration damping.

43. Lost Motion

Lost motion usually comes from play in gearing or mechanical linkages which makes a proportional servo behave like an on-off servo without dither. If there is a small error, the actuator will respond, but the load will not move until all the lost motion has been taken up. By this time, the actuator will have picked up speed, and it will be inclined to bump the load past the proper position to one side or the other. If jitter of this sort is to be avoided, the servo must have a large dead space, and this is undesirable. Lost motion is avoided best by precision of manufacture, although there are other methods of eliminating it, two of which are discussed in paragraph 51.

44. Summary and Review Questions

a. Summary.

(1) The positioning servo is representative of a large class of servos used in military applications. All positioning servos are comprised of the following elements:

(*a*) A load, which is a heavy mass positioned by the servo in response to an external position order.

(*b*) An actuator, which is the device that moves the load.

(*c*) A controller, which controls the operation of the actuator.

(*d*) A follow-up, which repeats the actual load position to the sensing element.

(*e*) A data receiver, which repeats the external position order to the sensing element.

(*f*) A sensing element, which compares the external position order and the actual load position and develops an error signal.

(2) The error signal is the difference between the actual load position and the externally ordered position. The error signal, like the inputs, may be any one of several types, such as an electrical, a mechanical, or a hydraulic error signal.

(3) There are three representative methods of servo control—on-off, stepwise, and proportional.

(4) Servo systems must be stabilized to prevent oscillation. This is sometimes accomplished by viscous damping. In the case of proportional servos, an electrical damping signal normally is used. Anti-hunt controls often are provided to prevent overdamping.

(5) Certain error considerations are present in most servo systems, including dead space, jitter, noise, instrumental error, velocity lag, and acceleration lag.

(6) Dead space in a servo results in inaccurate positioning of the load. It is reduced for an on-off servo by introducing dither, for a stepwise servo by a reduction in step size, and for a proportional servo by an increase in the error signal.

(7) Instrumental error is minimized by using coarse-fine systems and transfer circuits.

(8) Velocity lag is eliminated by addition of order-rate signal and, in the case of proportional servos, by error-rate damping.

(9) A rate servo is one that controls the rate of a load, rather than its position. It usually is operated with proportional control and, when so operated, is inherently stable.

(10) Proportional control, although more complicated than on-off or stepwise control, lends itself more easily to compensation for dead space and velocity lag, and therefore usually is used in military applications.

(11) A signal proportional to the first derivative of the error, which is the rate at which the error changes, may be used to obtain damping without introducing any velocity lag. A signal proportional to the second derivative of the error, which is the rate at which the first derivative changes, sometimes is used to provide intensified damping. A signal proportional to the integral of error also is used occasionally in viscous-damped servos to insure that the average error over a period of time is zero.

(12) Mechanical problems include springy coupling, which can be remedied by damping, and lost motion, which may be eliminated in several ways.

b. Review Questions.

(1) Name five error considerations normally present in servo systems.

(2) How is dead space in a servo counteracted?

(3) What is dither? What is jitter?

(4) What is rate servo?

(5) Name the elements that comprise a positioning servo.

(6) Define the term slewing rate.

(7) What is an error signal? Name three types.

(8) Name two methods of eliminating velocity lag.

(9) What type of control generally is used in military applications? Why?

CHAPTER 3

SERVO COMPONENTS

Section I. ACTUATORS

45. Torque

a. The behavior of a load moved back and forth by a positioning servo may be determined by noting that the force exerted on the load causes a change in the speed with which the load moves. If the load rotates instead of moving back and forth, it is convenient to make use of a concept of turning force called torque. Application of this force causes a change in the speed with which the load rotates. Torque is measured as the product of the applied force, by the distance between the axis of rotation and the line of action of the force.

b. In A of figure 20, A represents the axis of rotation, B and B_1 are the applied forces, the arrows represent the lines of action, and C and C_1 are the distances between the axis of rotation and the two lines of action. The unit of torque, therefore, is a compound one, and is generally expressed in the terms ounce-inches or pound-feet. The beam shown is balanced because the torques applied by the two weights are equal and oppositely directed, each weight applying a torque of 3 ounce-inches.

c. A method of measuring the torque output of a motor is illustrated in B of figure 20. It is possible to talk about the force exerted by the motor, since this is the quantity read by the spring balance; the motor, however, runs at a fixed speed because the driving torque on the shaft is balanced exactly by the load torque applied by the brake shoe. If the radius of the brake drum were increased—equivalent to increasing the distance between the axis of rotation and the line of action—the same torque would be applied by a lighter force, and the spring balance would have a lower reading. Therefore, it is desirable to discuss the torque output of a motor instead of the force output. The torque output of a motor depends on the power supplied to it, and on the speed at which it runs. The torque output of a motor at zero speed is called the stall torque of the motor, and the speed at which the torque output drops to zero is called the no-load speed.

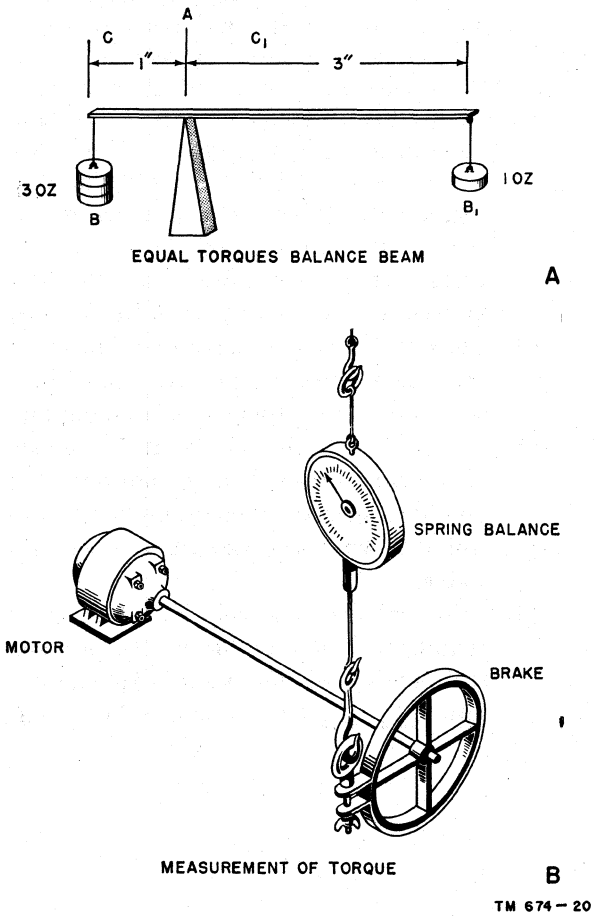


Figure 20. Torque balance and measurement.

46. D-C Motors

In general, d-c motors develop higher stall torque than a-c motors and, therefore, are used more often for servos driving heavy loads such as gun turrets and radar antennas. Figure 21 is

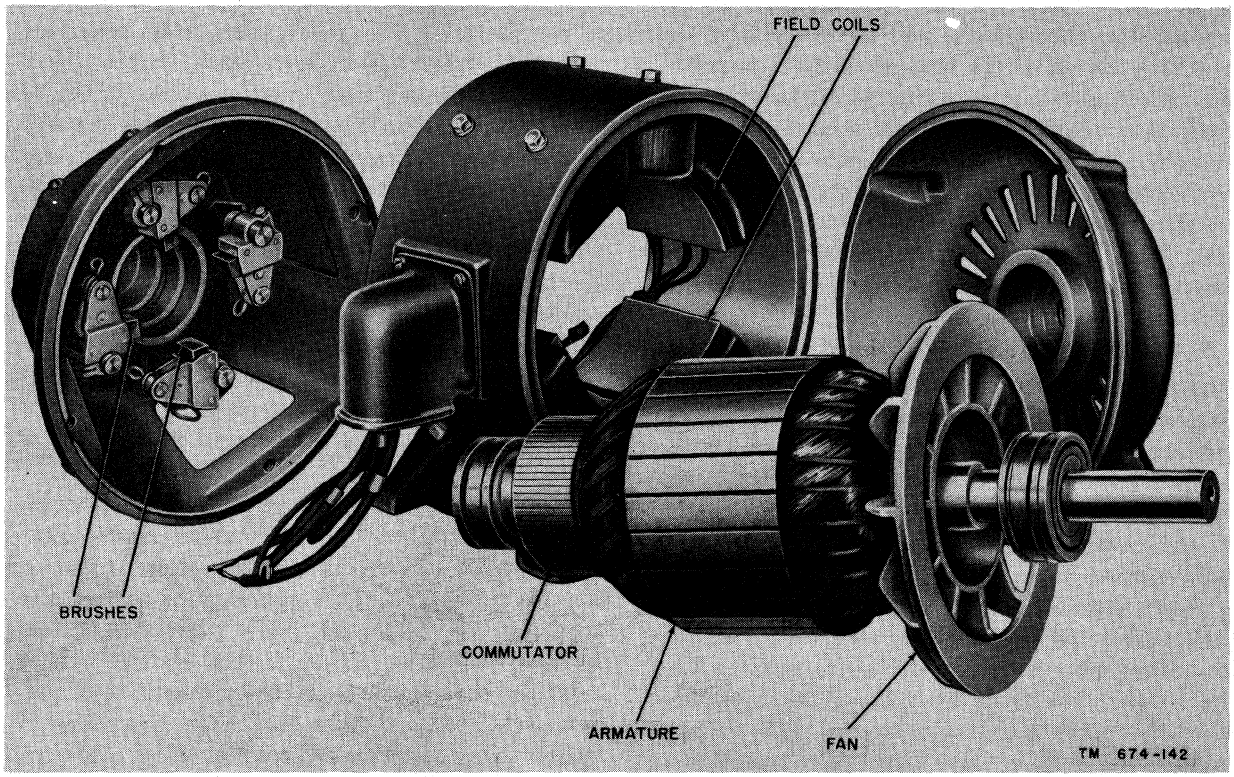


Figure 21. Typical d-c motor.

a photograph of one type of d-c motor. D-c motors are used also where large amounts of a-c power are not readily available, as in aircraft installations.

a. Basic Theory. The basic parts of a d-c motor are a field structure and an armature (fig. 22). In very small motors, the field may consist of a suitably shaped permanent magnet, but is usually an iron structure with coils which magnetize it when current is passed through them. The armature consists of a series of coils wound on an iron core. The arrangement is such that some of the armature coils lie in the magnetic field set up by the field structure. Current is carried to the armature coils through brushes and a commutator, which pass current only through the coils that lie in the magnetic field. Figure 22 shows the field structure as two magnetic poles. The armature is shown as a single coil, and its iron core is omitted. When current is passed through the armature coil, one side is pushed up by the interaction between the current and the magnetic field, and the other side is pushed down. These forces, acting on the two sides of the coil, develop a torque which tends to turn the motor shaft. As

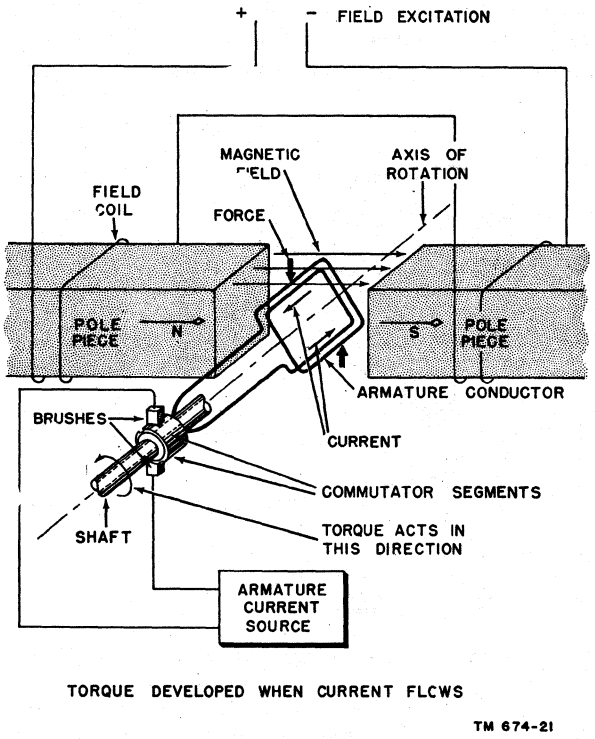


Figure 22. Torque produced in basic d-c motor.

the armature turns through 180°, the direction of current flow through the coil is reversed by the switching action of the brushes and commutator, so that the direction of torque is unchanged. In practice, a number of coils are used, and each is energized only during a small part of a revolution. The motor may be reversed either by reversing the armature current or by reversing the magnetic field; reversing both armature current and magnetic field simultaneously leaves the direction of the torque unchanged.

b. Back EMF (Electromotive Force). When a conductor moves at right angles to a magnetic field, maximum voltage is induced. The voltage induced will depend on the angle at which the conductor moves through the field (fig. 23). Because of the physical arrangement of a d-c motor, it can be used also as a d-c generator, the armature being turned by an external power source. Voltages are induced in the coils as they move past the magnetic poles of the field structure. Voltage is induced also when the armature is turned by the torque developed by the armature current when the motor is used as a motor. This voltage, called *back emf*, is in a direction opposing the armature-driving voltage and always is present in a d-c motor. For example, if 10 volts is applied to the armature of a d-c motor, current flows and torque is developed. If the motor now is prevented from rotating, the torque output will be the

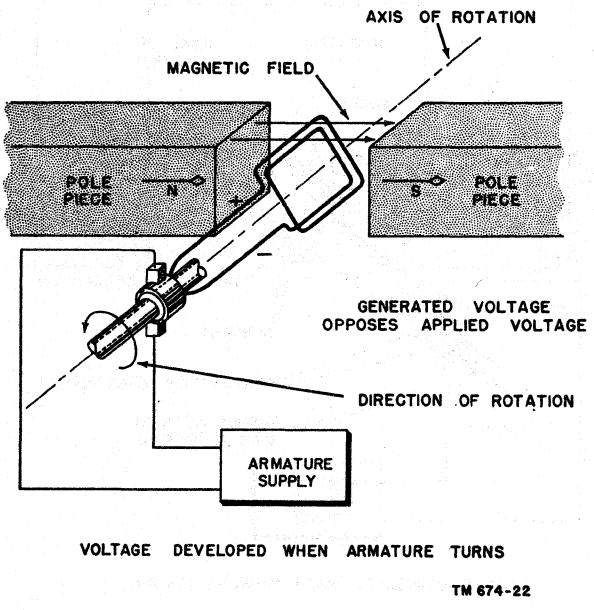


Figure 23. Induced voltage in d-c motor used as a d-c generator.

stall torque of the motor for an input of 10 volts. If the motor is allowed to turn, a back emf of perhaps 2 volts will be developed. Since this 2 volts of back emf is in a direction opposing the 10 volts applied to the armature, only 8 volts is available to cause current to flow through the armature. The torque output at this speed with 10 volts input is thus the same as the stall torque with 8 volts input. As the motor speed increases, the back emf also increases; when the back emf reaches 10 volts, there will be no armature current and no torque output. The speed at which the back emf and the armature current cancel each other is called the no-load speed and, in this case, is referred to as the no-load speed with 10 volts input.

c. Armature Control. In a small d-c motor with field supplied by a permanent magnet, the only method of control is by variation of the armature voltage. This control method is used also for large motors having fields which are excited by field windings, although field control can be used for such motors. Armature control is preferred for servo motors because of the shape of the resulting torque-speed curves. With armature control, at any speed the torque output is increased as the voltage applied to the armature is increased. The curves shown in figure 24 show how the torque output is affected by back emf with a constant field excitation. The stall torque of the motor is seen to be proportional to the voltage applied to the armature, the zero voltage curve passes through the origin, and the other curves intersect the torque axis at heights proportional to the voltage. For any applied voltage, the back emf and the consequent torque reduction are proportional to speed, so that each curve is a straight line showing a torque which falls off uniformly as speed is increased. Since back emf and torque reduction for a given speed are the same for any applied voltage, all curves drop by the same amount for a given change in speed and are, therefore, parallel. The curves show that torque—in the opposing direction—is developed even when no voltage is applied to the armature, because back emf causes current to flow through the armature in a direction causing a negative torque opposing the motion as long as the armature is connected to a circuit through which current can flow.

d. Field Control. Field control of the d-c motor normally is not used for servo motors. One

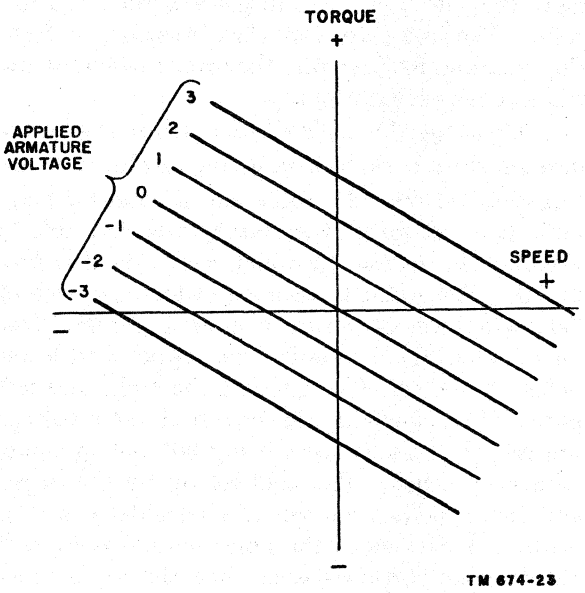


Figure 24. Torque-speed curves for armature control of d-c motor.

reason is the shape of the torque-speed curves (fig. 25). Another reason is that the retentivity of the field structure causes a small magnetic field to remain after the field voltage has been reduced to zero. The motor then has a small torque output which is objectionable in servo applications. The curves are explained easily if it is assumed that the armature is connected to a source of fixed voltage. Since the stall torque is proportional to the applied field voltage, the zero-voltage curve passes through the origin and the others intersect the torque axis at heights proportional to the voltages. For a given field voltage, back emf and consequent torque reduction are proportional to the motor speed. Each curve is then a straight line showing a torque which falls off uniformly with increasing speed. Now consider the curves corresponding to two field voltages, one twice as large as the other. For a given speed, back emf at the high field voltage will be twice as great as that at the low field voltage, since the magnetic field is twice as great. The reduction in armature current will be twice as great for the high field voltage as for the low field voltage. However, the reduction in torque is proportional to the product of the field voltage and the reduction in armature current, and consequently the high voltage curve (which shows twice the stall torque of the low voltage curve) intersects the speed axis at a no-load speed one-half as large. An examination of the curves shows that for low torques (light loads) the speed of the motor *decreases* when the field voltage is increased. The same effect, considered from a constant-speed viewpoint, results in a decrease in torque output for increased field voltage when the motor is running near its no-load speed.

e. Split-Field Series D-C Motor. This motor has two sets of field coils wound in opposite directions. The direction of rotation, therefore, is determined by choosing the appropriate field winding and exciting it in series with the armature. A split-field d-c motor of this type is shown in figure 26; A of figure 27, shows a typical schematic representation. In terms of physical dimensions required for a motor having a given torque output, this motor is not as efficient as a single-field motor of the same output. It is simple to control, however, and is used frequently in low-power servos. As in any d-c motor, the stall torque is proportional to both the armature current and the strength of the magnetic field. Since the field strength is proportional to the field current, which is the same as the armature current, the torque is proportional to the square of the current. At zero speed there is no back emf, and the current is proportional to the applied voltage; consequently, the stall torque is proportional to the square of the applied voltage. Assume that the motor is running at some speed and developing output torque. If its speed is increased slightly, the back emf will increase. The change in the back emf is proportional to the magnetic field, and therefore propor-

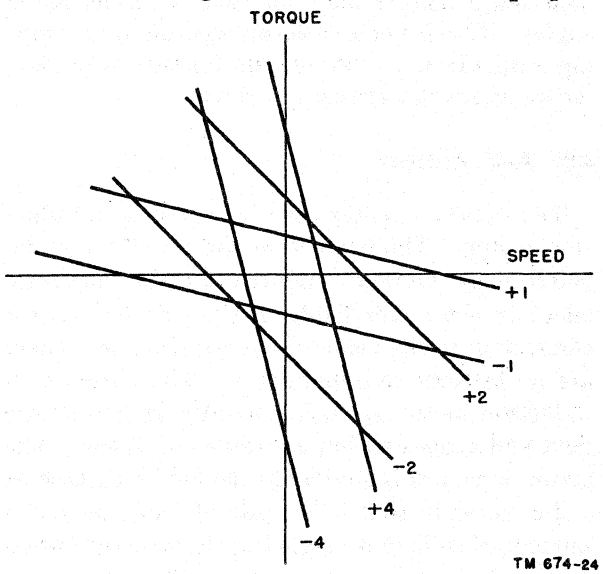


Figure 25. Torque-speed curves for field control of d-c motor.

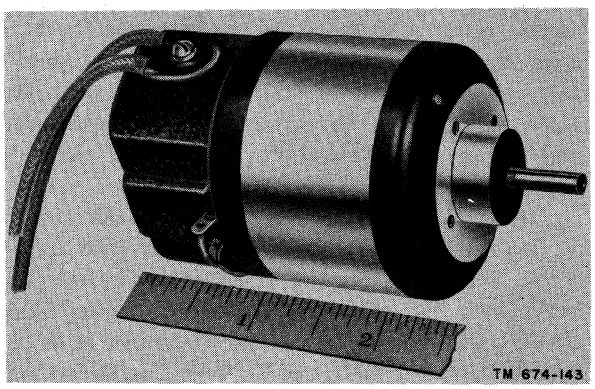


Figure 26. Split-field d-c motor.

tional to the current. Since the back emf bucks the applied voltage, there will be a drop in current as the speed is increased. The drop in current is proportional to the back emf, and therefore proportional to the current flowing through the motor. For any applied voltage, the torque falls with increasing speed but, because of the reduction in current, it falls more slowly at high speeds than at low speeds. This effect is shown in the torque-speed curves in B of figure 27.

47. A-C, D-C Motors

Any d-c motor will run on alternating current if the phases of the field and armature currents are adjusted properly. This may require phase-shifting networks, since the impedances of the field and armature may not have the same phase angles. This is not an efficient method of developing torque from a-c power, and for this reason a-c, d-c motors rarely are used in servos.

48. A-C Motors

The usual a-c motor used in servos is an induction motor. The current in the armature is developed by voltages induced by the magnetic effect of the motor field. No physical electrical connection to the armature is required, and there are no brushes or commutator. The parts of an induction motor are not generally known as the field and armature, but as stator and rotor. The stator structure is similar to the field structure of a d-c motor in that it is made of iron and has a number of coils that magnetize the structure when current is passed through them. The rotor sometimes is wound on an iron core, but it consists more frequently of a cup in place of the armature coils. The iron rotor core then is separated from the rotor and fixed, so that the rotor revolves while the core remains stationary.

a. Rotating Magnetic Fields. Since the torque developed by an induction motor results from interaction between the rotor and a rotating magnetic field set up by the stator, it is desirable to examine the method by which such a field is produced. The stator is assumed to have two sets of field windings, as shown in A of figure 28. One set of windings magnetizes the upper and lower poles, the other set magnetizes the right and left poles. The two fields are connected to a-c voltage sources, the two voltages being 90° out of phase with each other. The field set up by the upper and lower poles then varies sinusoidally and is directed from one of the poles toward the other. Its direction reverses each time the a-c current in the windings reverses. The right and left poles set up a similar field, which is 90° out of phase with the first field. The two fields add to form a resultant field. The direction and strength of this

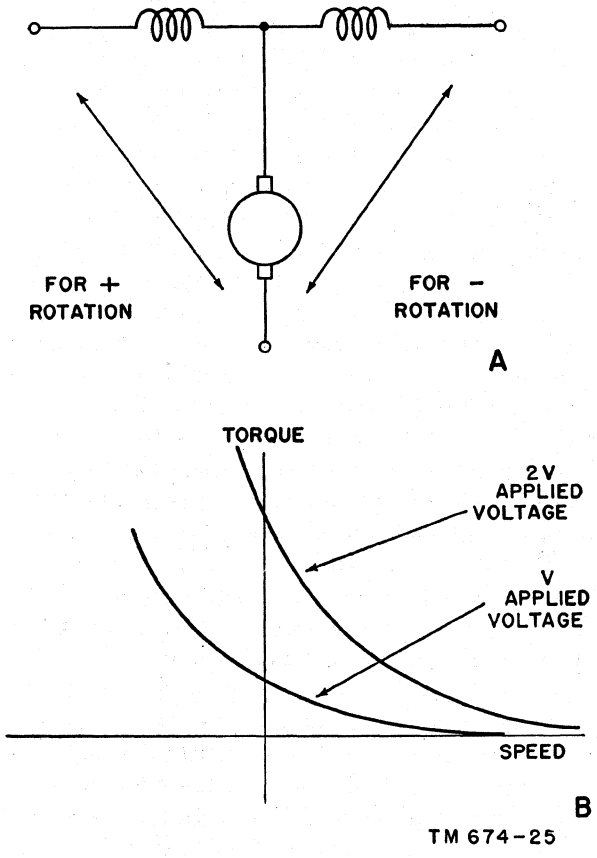


Figure 27. Typical torque-speed curves.

field may be determined by a method called vector addition. Each field is represented by a small arrow, called a vector (B of fig. 28), which has a direction the same as that of the field and a length proportional to the strength of the field. Vectors are drawn for the fields set up by the upper and lower poles and by the right and left poles. These vectors form the sides of a parallelogram, and the vector for the resultant field is the diagonal of the parallelogram. If the resultant field is determined in this way for various instants during an a-c cycle, it can be seen that it is a field of constant strength whose direction changes steadily. The vector for the resultant field has a fixed length and turns at a uniform rate, making one revolution for each a-c cycle. The resultant field vector is shown for various parts of the cycle in B of figure 28.

b. Multipolar fields. In some cases, each set of stator windings magnetizes more than one pair of

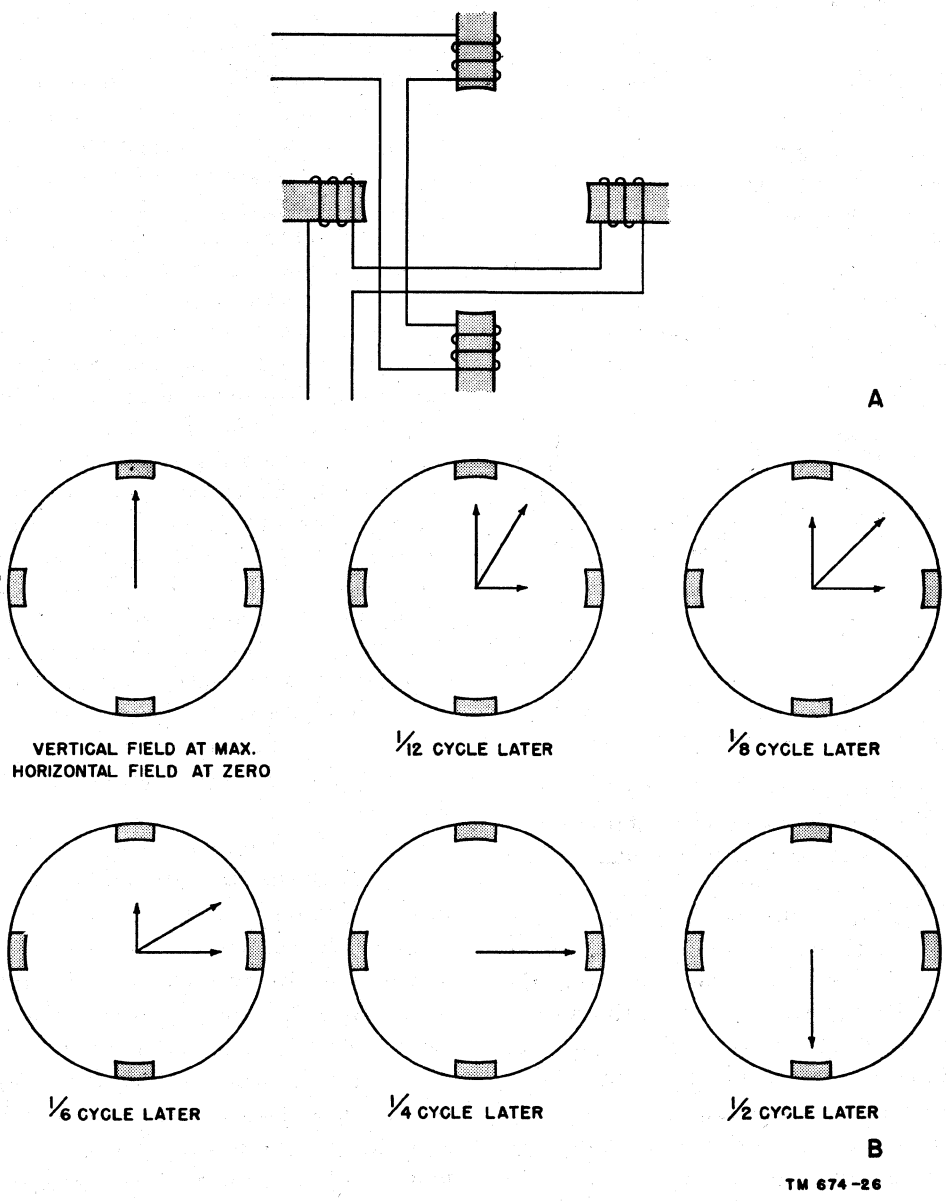


Figure 28. Rotating magnetic fields.

poles. Figure 29 shows what happens when there are eight poles, two pairs for each winding. The resultant field is shown in A and B; also in C and D, with the rotor core in place. When each stator winding magnetizes two sets of poles, the resultant field rotates only one-half revolution for each a-c cycle.

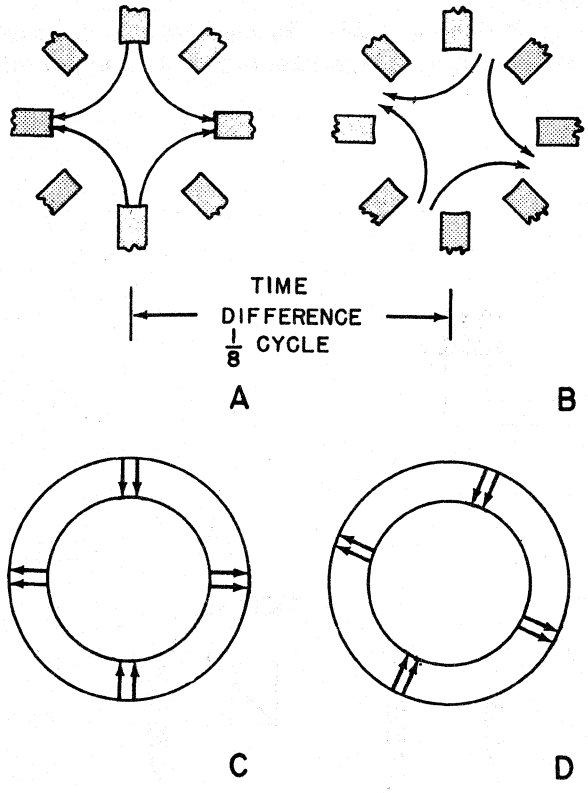


Figure 29. Multipolar field.

c. Effect of Unequal Field Excitation. The resultant field, when the two sets of stator windings are not equally excited, may be explained best by considering two separate resultants in the following way. Each of the original fields is directed one way or the other along a line between the two poles which cause the field, and the strength of the field is proportional to the current flowing in the appropriate windings. A field of this sort, the strength of which varies sinusoidally, may be considered as the resultant of two separate fields, rotating in opposite directions and both having the same strength (fig. 30). The field from the upper and lower poles is, therefore, the resultant of two fields, one rotating clockwise and the other counterclockwise, both having the same strength. The field of the right and left poles can be considered in the same way. If the voltages applied to the two sets of stator windings are 90° apart in phase, the field vectors rotating in one direction will have a resultant equal to the arithmetic sum of their lengths, since both point in the same direction. The vectors rotating in the other direction will have a resultant equal to the arithmetic difference, since they point in opposite directions. The counterclockwise rotating vectors are shown as adding, the clockwise vectors as subtracting. One set of windings, called the main field, is connected to an a-c line. The other set, called the control field, is connected to the output of the controller of a servo. The resultant field when both sets of windings are energized is then the same as the resultant of two rotating fields, one having a strength proportional to the sum of the main and control field excitations, the other having a strength proportional to the difference between the excitations. If the phase of the control field excitation is reversed, the strengths of the two rotating fields are interchanged, and any torque produced by the fields has its direction reversed.

d. Voltages Induced in Rotor. Each of the rotating magnetic fields, referred to as the forward field and the backward field, induces voltages in the rotor (fig. 31). The voltage is proportional to the strength of the field and to the velocity of the rotor relative to the field. When the rotor turns at the same speed as the field (synchronous speed), no voltage is developed. As the rotor speed falls below synchronous speed, the induced voltage increases uniformly. As the rotor speed changes, its speed relative to one of the rotating fields is increased, and its speed relative to the other is decreased.

e. Torque Developed by Forward Rotating Field. Both the forward and backward magnetic fields will induce voltages in the rotor, and both of the induced voltages will cause current to flow. The torque developed by the forward field is then the result of interaction between the field and the two induced currents. Fortunately, the positions on the rotor at which voltages are induced by the rotating field move around the rotor with the field, and the current flowing because of the voltage moves in the same way. Therefore, any rotor current induced by the backward magnetic field rotates in the direction of the backward field, and

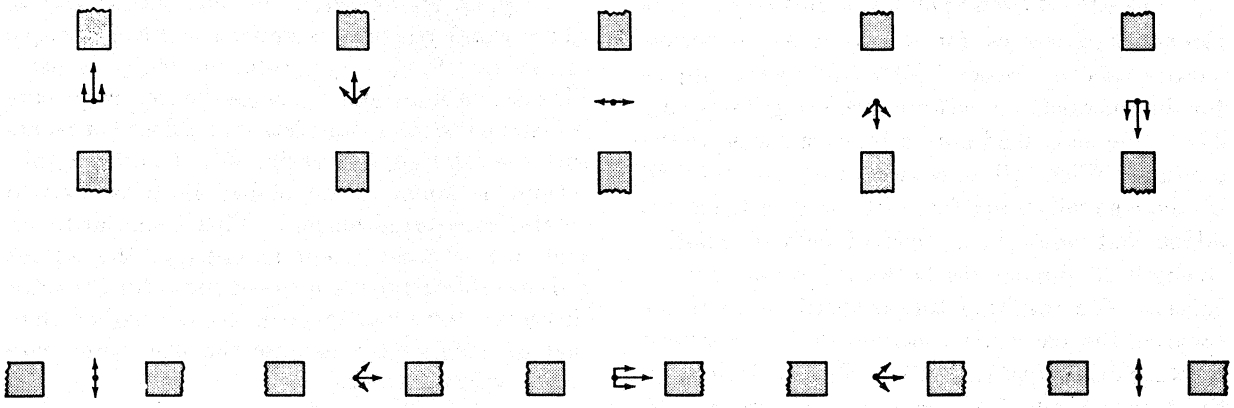
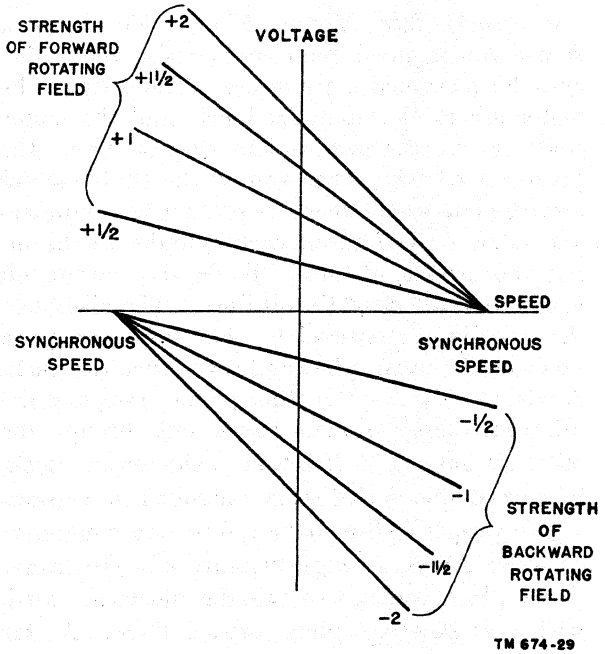


Figure 30. Equivalence of pulsating and rotating fields.

TM 674-28

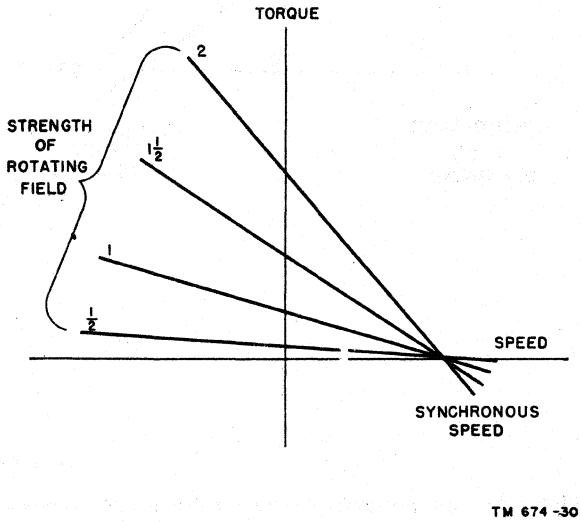
the interaction between such a current and the forward magnetic field (which rotates in the opposite direction) develops an alternating torque with an average value of zero. The torque developed by the forward rotating magnetic field depends, then, only on interaction between this field and the rotor currents which the field induces. With a high-resistance rotor, the current is in phase with the voltage, and the torque is proportional to the product of the current and the field strength. With a low-resistance rotor, in which rotor reactance is important, the situation is much more complicated. Such a motor, however, has low stall torque and rarely is used in servo applications.



TM 674-29

Figure 31. Voltages induced in rotor of a-c motor.

The shape of the torque-speed curves (fig. 32) for the forward rotating field follows from the voltage-speed relations. For any field strength, there is no voltage induced at synchronous speed, and consequently no torque. All of the torque-speed curves for the forward field, therefore, show synchronous speed as the no-load speed. In each case, the induced voltage and consequently the torque increase uniformly as the rotor speed falls below synchronous speed, and all of the curves are straight lines. At zero speed, the voltage and the current are proportional to the rotating field. The torque is proportional to the current and the field, and so proportional to the square of the field. The set of curves thus consists of straight lines showing stall torque proportional to the square of the field, and no-load speed equal to synchronous speed.



TM 674-30

Figure 32. Torque-speed curves for forward rotating field.

f. Two-Phase Induction Motor Behavior. The torque-speed curves for a two-phase induction motor (*c* above) are obtained by adding the torques for the forward and backward rotating fields (fig. 33). The main field normally is connected to the a-c line. With full excitation of the control field by the controller, the forward rotating fields are added and result in a forward field of relative strength 2, whereas the backward rotating fields cancel. The resulting torque-speed curve is the same as the one shown earlier for the forward rotating field alone (fig. 32). With ½ excitation, the forward field has a relative strength of 3/2, and the backward field has a relative strength of ½. Addition of the torque-speed curves shows that the stall torque is proportional to the excitation of the control field, which is a desirable characteristic for servo work. With partial excitation, the torque-speed curve falls uniformly from stall torque to a no-load speed that is somewhat less than synchronous speed.

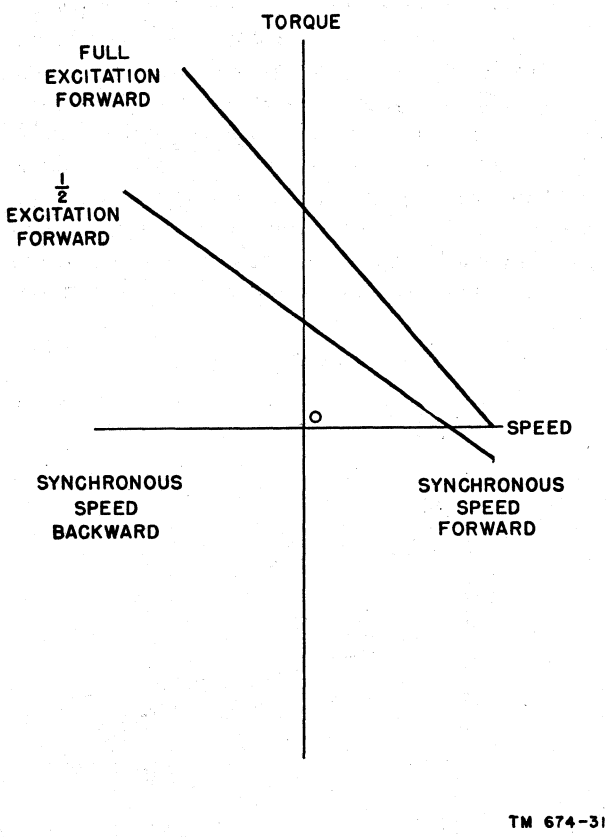


Figure 33. Torque-speed curves for two-phase induction motor.

g. Types of Rotors. For computing servos, where rapid response is desired and some torque can be sacrificed, a cup rotor normally is used. This has very low inertia, since the iron rotor core is fastened to the motor frame and does not rotate with the rotor cup (A of fig. 34). In other applications, a wound rotor, shown in B is used to obtain more torque output. This is similar to the armature of a d-c motor except that the several coils are shorted to form closed paths for the rotor currents. The inertia is of course higher than that of a cup rotor because the iron rotor core moves with the rotor.

49. Hydraulic Actuators

Hydraulic actuators are used frequently, particularly in aircraft installations, because of their relative simplicity, but where continuous operation is required hydraulic mechanisms have little to offer over electric motors. On the other hand, when operation is required for short periods separated by long intervals, it is possible to obtain tremendous output from a small hydraulic actuator by using a hydraulic accumulator (fig. 35) as a source of power. Oil is stored in a bag, and air pressure in the body of the accumulator forces the oil out to the actuator at high pressure. The chief merit of an accumulator is that it may be filled with oil by a very small pump if the time for filling is sufficiently long.

a. Swash-Plate Motor. Figure 36 shows a four-cylinder swash-plate motor; six- and eight-cylinder motors also are in use. The body of the motor serves as a cylinder block, and the motor shaft carries the swash-plate against which the pistons act. The other end of the shaft carries a valve plate which uncovers ports in the cylinders and alternately connects each cylinder to the input and output oil lines. To develop torque, oil is admitted to one of the oil lines. The pistons in the cylinders connected to that line then push down on the swash-plate and try to turn the shaft. As the shaft turns, the other pistons rise, and the oil from these cylinders passes out through the other oil line. The direction of the torque, clockwise or counterclockwise, is controlled by connecting the proper oil line to the hydraulic accumulator or other source of high-pressure oil. In larger swash-plate motors, two cylinder blocks are used, with a single swash-plate between them. As far as the servo is concerned, the swash-plate motor

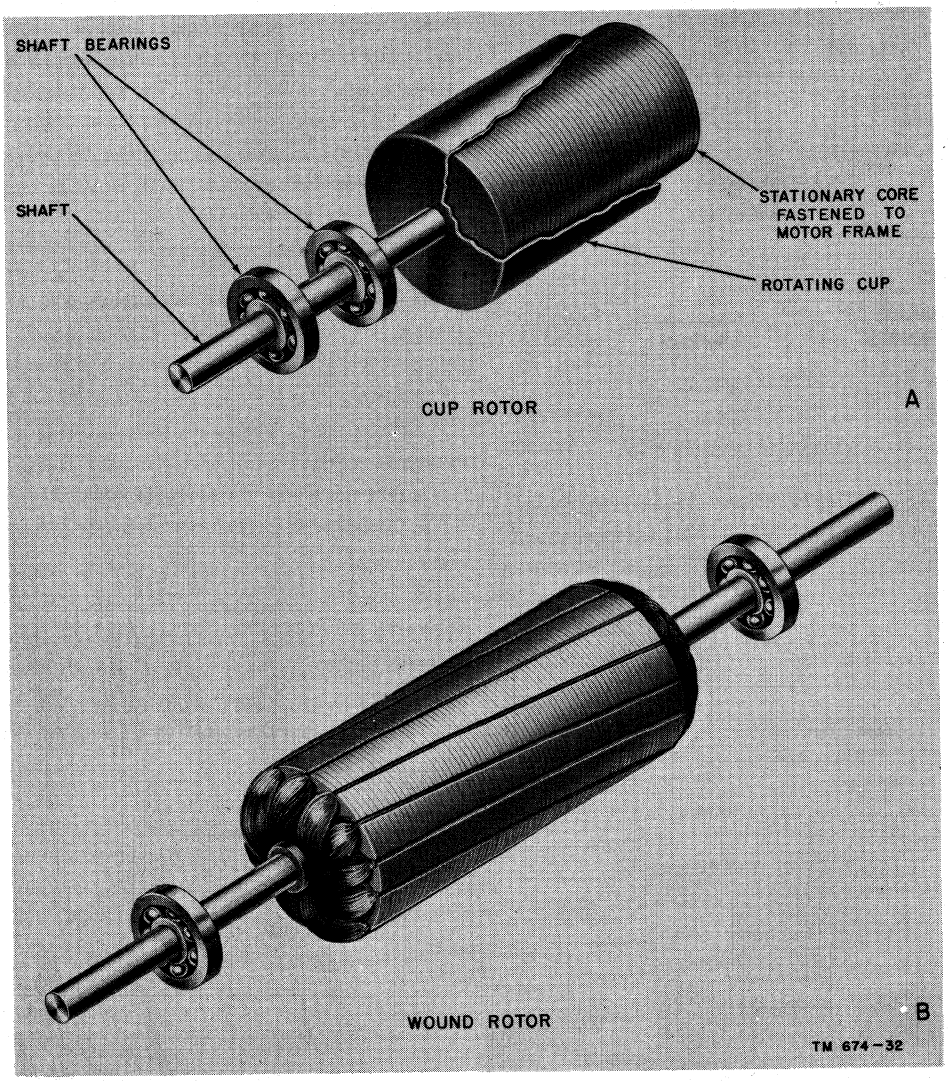


Figure 34. Types of rotors.

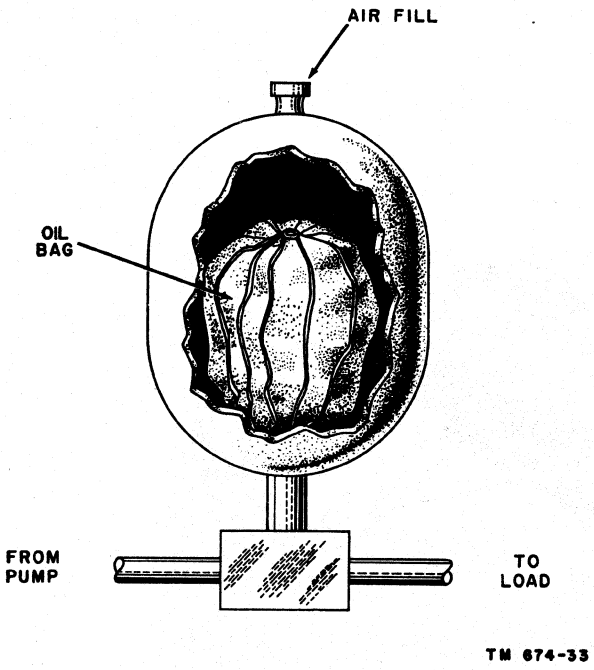


Figure 35. Hydraulic accumulator.

behaves like any other motor. It is controlled by a hydraulic valve (par. 58). The torque-speed curves are all straight lines, the curves corresponding to different valve settings all pass through approximately the same stall torque point, and the no-load speed for each curve is proportional to the amount by which the valve has been opened. The major merit of the swash-plate motor is that it can provide a large amount of torque for a short period of time by making use of the energy stored in a hydraulic accumulator.

b. Hydraulic Ram. The hydraulic ram (fig. 37) is useful when back-and-forth motion is required, because it can be connected directly to a load without gear train. It is operated by admitting oil under high pressure to one side of the piston and connecting the cylinder on the other side to a low-pressure oil line. The force-speed curves for the ram are similar to the torque-speed curves for the swash-plate motor.

50. Other Actuators

A number of other actuators are used in servo work, including bellows which exert force when connected to a high-pressure air line, and heating elements which serve as actuators in temperature control servos; however, these actuators seldom are seen in military applications. Two types occasionally used are described below.

a. Solenoid Actuator. A solenoid actuator (fig. 38) consists of a coil with an iron core. When current is passed through the coil, the core is drawn toward a central position, and if there is an obstacle which prevents it from moving, it exerts

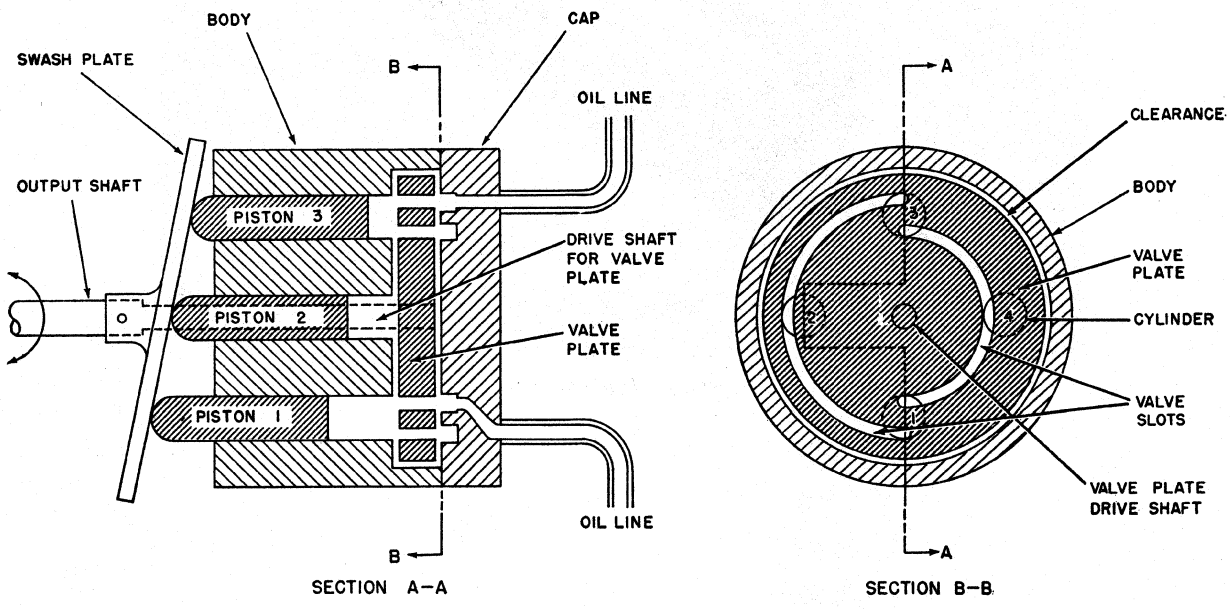


Figure 36. Swash-plate motor.

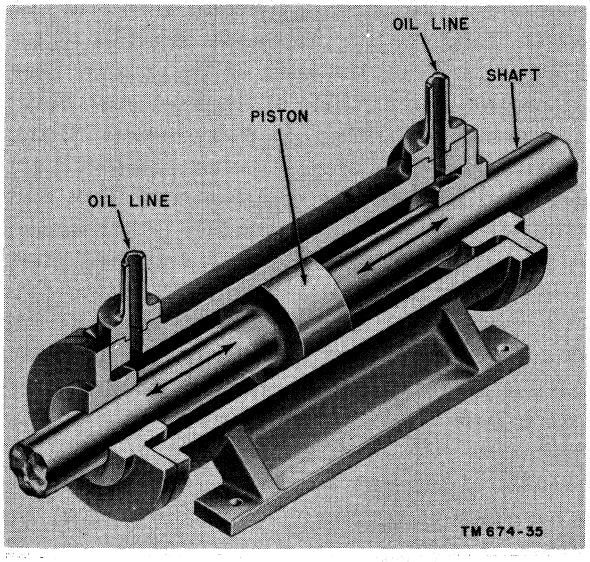


Figure 37. Hydraulic ram.

force on the obstacle. Solenoid actuators are used in some aircraft voltage regulators. A push rod fastened to the core exerts force on a stack of carbon disks, changing the electrical resistance of the stack.

b. Microsen Elastic-Restraint Motor. A microsen (fig. 39) consists of a stator with two pairs of poles and an iron rotor. One or both of the field windings may be energized. This produces a magnetic field, and the rotor tends to line itself up with the field. Consequently, a torque is developed at the rotor shaft when the rotor is not alined with the field; for small angles this torque is proportional to the field strength and the angle of misalinement. The microsen, when used as an elastic-restraint motor, acts like a spring on the rotor shaft, the stiffness of the spring being determined by the voltage applied to the fields.

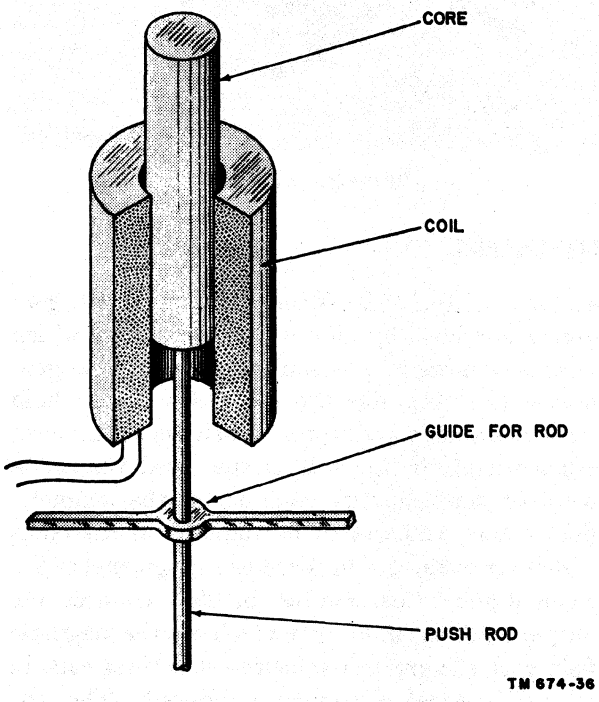


Figure 38. Solenoid actuator.

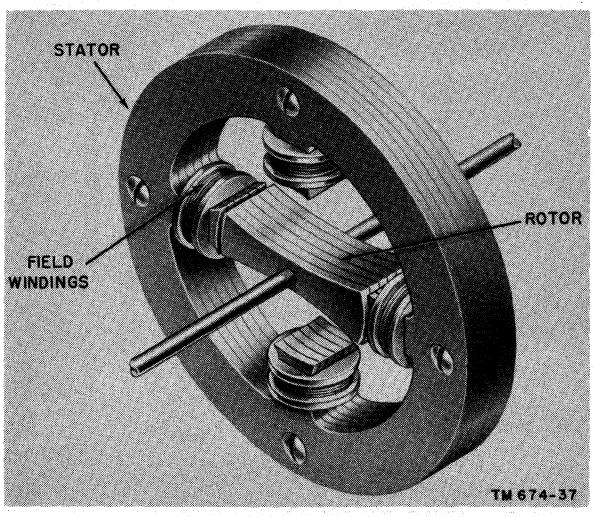


Figure 39. Pictorial of microsen elastic-restraint motor

51. Antibacklash Devices

As explained in paragraph 43, backlash or lost motion in a servo is undesirable. Backlash is minimized as far as possible by good design and careful production, and the remainder generally can be eliminated substantially by one of the methods described below.

a. Preloading Motor. In figure 40, the mechanical linkage of a servo is shown as a gear train connecting the actuator to the load. Lost motion is overcome by preloading the gear train—that is, adding a steady load which takes up slack by always acting in the same direction. The preloading device is a small motor which exerts just enough torque to take up the lost motion. If the travel of the load is limited, a spring may be used instead. This method, although simple, is undesirable since it causes the servo to operate differently in the forward and reverse directions. In one direction, the actuator is aided by the preloading device; in the other direction it is opposed. If

the torque of the preloading device is large, the servo may be overdamped for motion in one direction and underdamped for motion in the other direction.

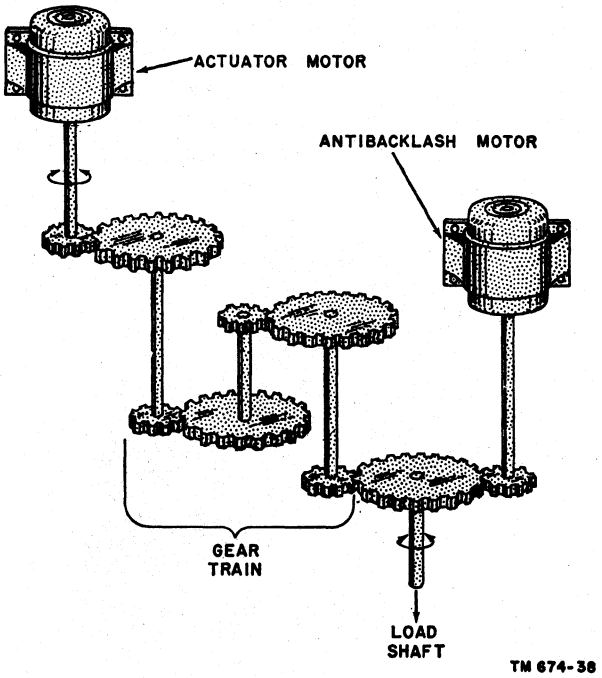


Figure 40. Antibacklash motor.

b. Split Gearing. A split gear consists of two parts—one, the fixed gear, is secured to the shaft; the other, the free gear, is free to rotate on the shaft. The two parts are connected by springs, as shown in figure 41. The teeth of a normal gear meshed with a split gear are pinched between the teeth of the two parts of the split gear, and lost motion is eliminated. When the direction of rotation is such that the teeth of the external gear are pressed against those of the fixed gear, operation is the same as that of a pair of normal gears. For rotation in the other direction, the forces are developed between the external gear teeth and those of the free gear. Torque then is transmitted by the springs of the split gear, and these must be reasonably stiff if lost motion is to be avoided. This requirement on the springs limits the use of split gears to light-duty servos. In practice, it is not necessary to use split gears except at the load end of the gear train. The last one or two meshes use split gears, and lost motion in the remainder of the gear train usually is so small as to have negligible effect on the performance of the servo.

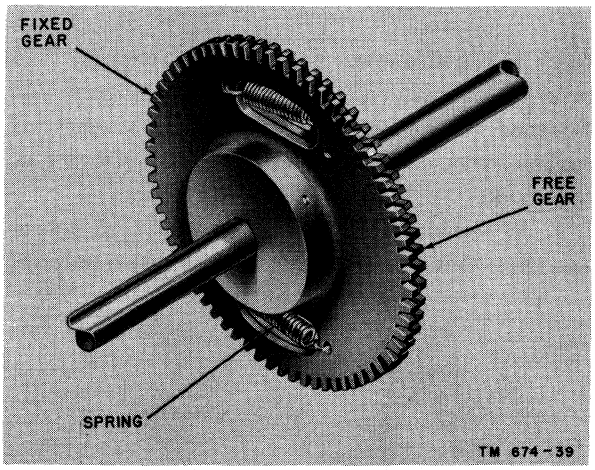


Figure 41. Split gear.

Section II. CONTROLLERS

52. Ward-Leonard Drive

One of the more usual control systems for a high-power d-c servo motor is the Ward-Leonard drive. This control system consists of a d-c generator, the output of which varies as the generator field excitation is changed. The error signal is used to excite the generator field, either directly or through an amplifier, and the generator output is used to power the servo motor.

a. D-C Generator Theory. The theory of the d-c generator was covered during the discussion of back emf generated in a d-c motor (par. 46*b*). Torques and voltages for a d-c machine used as a motor are the same as those for one used as a generator. In the Ward-Leonard drive, a d-c generator is turned by an a-c or a d-c motor, which runs at a more or less constant speed. The generator (fig. 42), like the d-c motor, has a field structure and an armature. When the field, shown schematically in figure 43, is energized, the movement of the armature coils across the magnetic field causes voltages to be induced in the coils, which are connected to the various segments of the commutator. Commutator brushes connect the output leads to those coils which cut the magnetic field with the greatest velocity—it is these coils in which the greatest voltage is induced. The output voltage is proportional to the speed at which

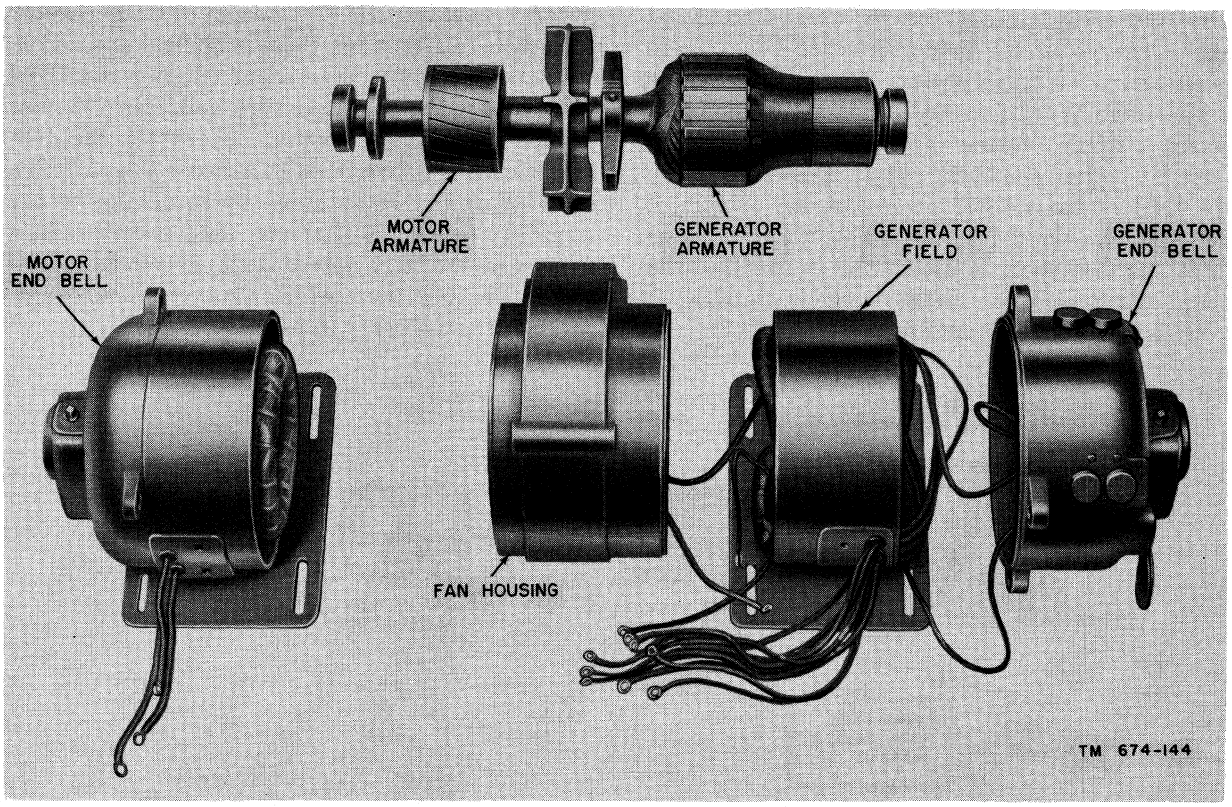


Figure 42. D-c generator.

the generator is rotated and to the magnetic field strength. Since the speed is more or less constant, the output voltage varies with the magnetic field and this, in turn, is proportional to the excitation current. Therefore, a d-c generator acts like an amplifier, the output voltage being porportional to the input current. The generator amplifies because the output power is much greater than the power required to energize the field. When output current flows through the load and, consequently, through the armature, torque is developed exactly as in a motor. It is developed in a direction opposing the rotation of the generator, and the driving motor therefore must do more work. The system is analogous to a vacuum-tube amplifier, the driving motor taking the place of the amplifier power supply.

b. Ward-Leonard Drive Theory. The Ward-Leonard drive, as used for control of a d-c motor, consists of a d-c generator and a driving motor for the generator. The signal input is used to excite the generator field, and the resulting generator output is used to power the d-c motor. Occasion-

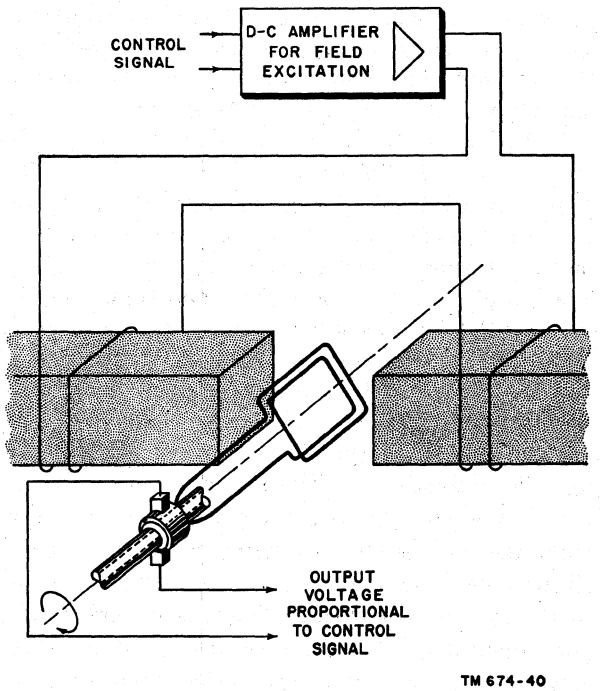


Figure 43. D-c generator schematic.

ally, the error voltage can be used directly to excite the generator field; at other times, it is necessary to use an amplifier. It is possible to use a two-stage Ward-Leonard drive as in figure 44, where a single driving motor turns two generators. The first generator output is used to excite the field of the second generator, the output of which drives the d-c motor. The Ward-Leonard drive, as described, is useful for controlling the speed of a d-c motor. In servo applications, however. it requires some modification.

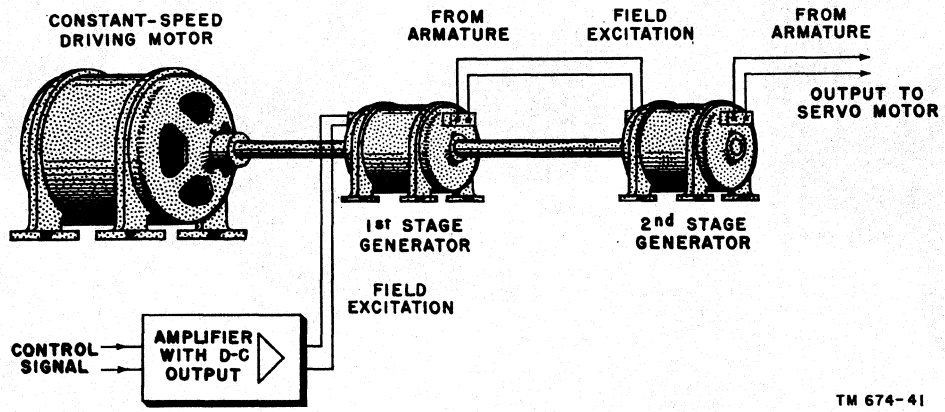


Figure 44. Ward-Leonard two-stage drive circuit.

c. Ward-Leonard Drive Modified for Servo Application. The problem involved in applying the Ward-Leonard drive to servos is caused by the tendency of a magnetic structure to remain magnetized after the magnetizing current is cut off. Because of this, the d-c generator has a small output even with no field excitation. This is extremely undesirable for servo applications, since the d-c motor—the actuator—will continue to develop torque in the absence of an error signal. The problem may be solved by additional windings on the generator field. If these are excited by a-c at a low level, the resulting magnetizing force, which will be alternating, will cause the average magnetization of the generator field to fall to zero when there is no excitation for the main field windings. The objection to this solution is the fact that a-c current in the auxiliary coils also causes the magnetic field to fluctuate slightly, thereby producing a small a-c component in the generator output. For this reason, small permanent magnets sometimes are mounted on the armature. These revolve with the armature, providing an alternating magnetizing force for the generator field, and the d-c output of the generator then falls to zero when there is no field excitation. However, since the permanent magnets are fixed with relation to the armature coils, they cannot induce voltage in the coils. Therefore, the generator output is free from an a-c component. The same effect can be obtained by so arranging the auxiliary windings that the field they produce rotates at the same speed as the generator armature. The manner in which a rotating field can be produced is discussed in paragraph 48*b*.

53. Amplidyne Drive

a. An amplidyne drive consists of a d-c generator rotated by an external motor, as shown in figure 45. The control voltage is used to excite the field of the generator and produces an output voltage at the armature brushes. The two brushes are connected, and the armature current which flows through this short circuit produces a second magnetic field. In figure 46, the field structure is shown as a pair of poles above and below the armature. The output voltage is induced in coils as they cross this field—that is, in coils which lie in a vertical plane—and appears at the upper and lower brushes. These are tied together and the resulting current flowing in the armature produces a second magnetic field at right angles to the first. The armature coils, in cutting this, have voltage induced in them and this induced voltage appears at the second set of brushes and is the output of the amplidyne drive.

b. In addition to the problems which occur with use of the Ward-Leonard drive, the amplidyne drive is subject to another difficulty. When load

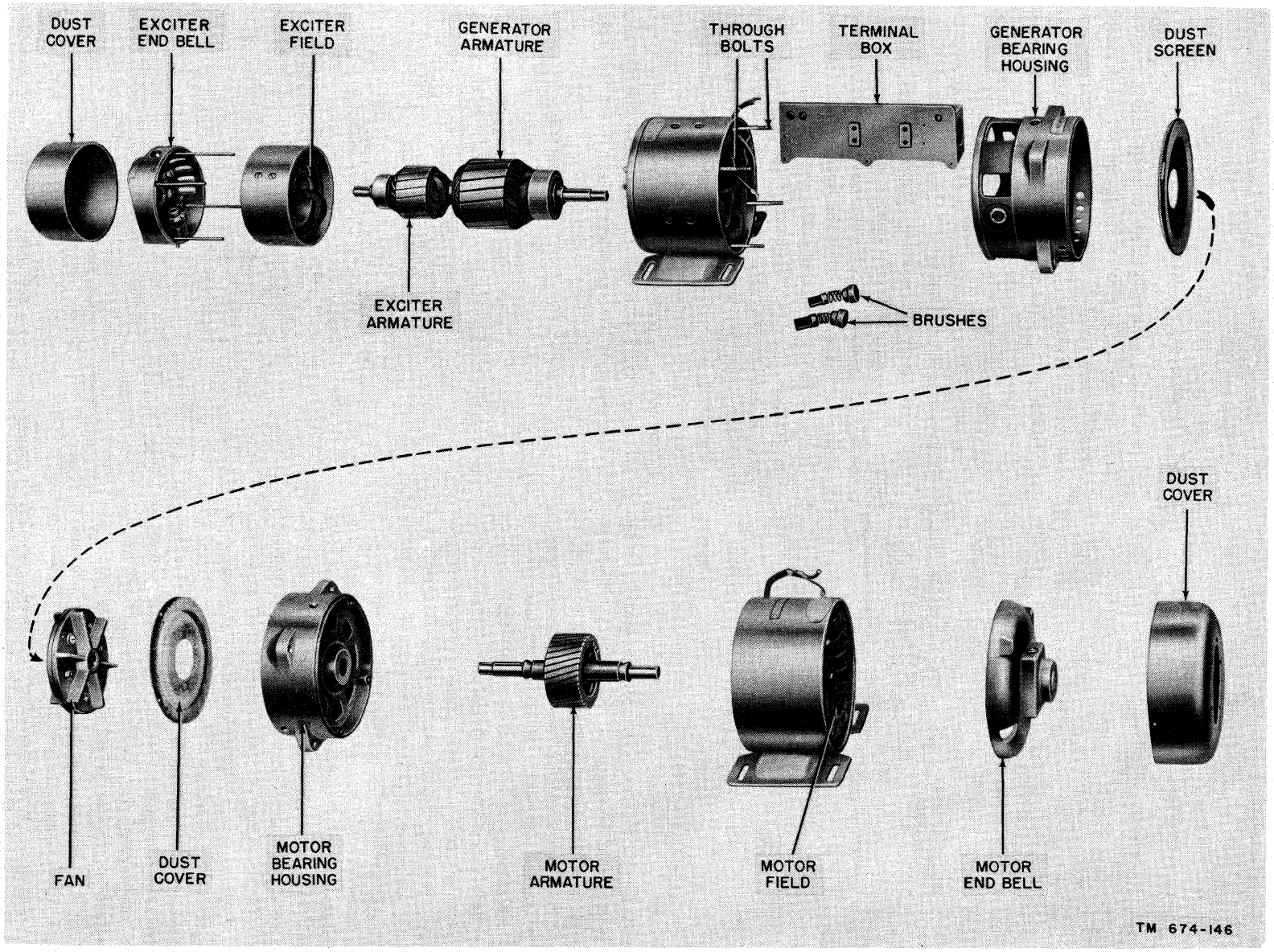


Figure 45. Amplidyne drive.

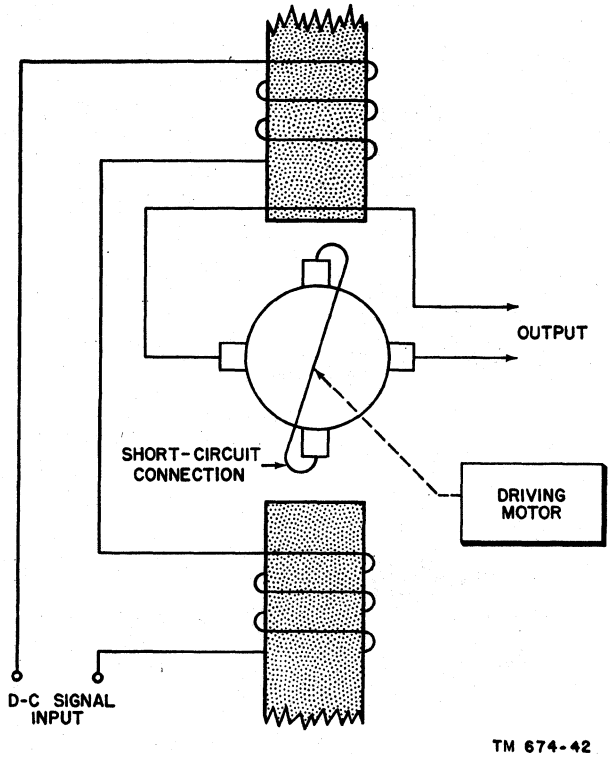


Figure 46. Amplidyne schematic.

current flows, it flows through armature coils which produce a magnetic field that bucks the main field. Therefore, the system has poor regulation; that is, the output voltage depends strongly on the output current. It is possible to correct this poor regulation by adding auxiliary windings to the field structure and passing the output current through them. The magnetizing force produced by passing the current through the auxiliary field can be made to balance that produced by the flow of output current through the armature. In some cases, this compensation is not added, and the torque-speed characteristics of the d-c motor controlled by the amplidyne are then altered. As back emf is generated in the motor, the current falls off. This causes the output voltage of the amplidyne to rise, so that the effects of back emf are partially canceled. The amplidyne drive is equivalent to a two-stage Ward-Leonard drive, but one piece of rotating equipment—the amplidyne—takes the place of the two d-c generators. This is not a great saving, however, since both the external driving motor and the d-c motor which is controlled are present in either case. Because the two stages of the Ward-Leonard drive are separate units, that system is slightly more flexible than the amplidyne drive with regard to impedance level, introduction of damping, and similar factors. Both drives are widely used for control of high-power d-c motors.

54. Thyratron Control

A circuit frequently used for controlling a split-field d-c motor is shown in figure 47. Its major merit lies in the fact that it permits control of a d-c motor from an a-c error signal without the addition of a phase-sensitive detector (a detector which produces a d-c signal having a polarity dependent on the phase of the a-c signal).

a. Thyratron Theory. The thyratron is similar to a vacuum tube but is filled with an easily ionized gas, usually mercury vapor. Most thyratrons have an indirectly heated cathode, a control grid, and an anode, but some have screen grids as well. Operation of the tube depends on the fact that any flow of electrons will ionize the gas molecules; that is, strip electrons from them. If the grid is held sufficiently negative, the tube will not conduct even though the anode is positive. With sufficiently high positive voltage on the anode for a given grid voltage, or with sufficiently small negative voltage on the grid for a given anode voltage, there will be enough electron flow to ionize some of the gas molecules. When this hap-

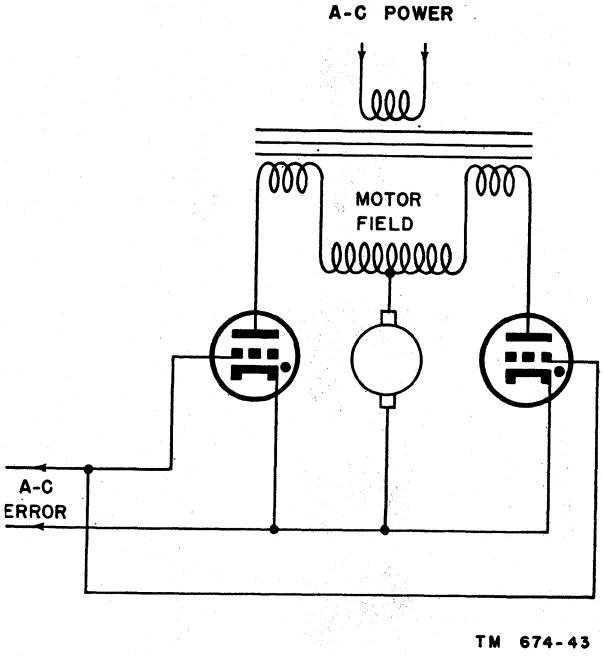


Figure 47. Thyratron control circuit for split-field d-c motor.

pens, the electrons which are stripped from the molecules become available for current carrying and they, in turn, ionize more gas molecules. The result is that the current rises rapidly to a value set by the external circuit, a value which will provide sufficient anode voltage that the electrons are accelerated to the point where they continue to ionize the gas molecules. This sudden rise of current is called firing and, when once the thyratron has fired, the grid loses all control. Current can be cut off only by dropping the anode potential to the point where ionization stops.

b. Thyratron Control Circuit for Split-Field D-C Motor. The split-field d-c motor runs in one direction when voltage is applied between one end of the center-tapped field and the free end of the armature. It runs in the other direction when the connection is transferred to the other end of the field. In the circuit shown in figure 47, a-c is applied between each end of the field and the free end of the armature, with a thyratron incorporated in each circuit. Since a thyratron passes current only in one direction, it will act like a half-wave rectifier in this circuit if it fires on each cycle (when its anode goes positive). If it is not fired, it will act like an open switch. The two a-c sources are 180° out of phase. The a-c error signal is in phase with one a-c source and 180° out of phase with the other. Reversing the sign of the error causes a phase reversal of the error signal. Suppose there is no error. The error signal will be zero. Each thyratron fires during the half-cycle when its anode is positive; the motor, therefore, is energized first in one direction and then in the other, and its net torque output is zero. In the presence of an error signal, the grid of one thyratron will swing in the positive direction when the anode swings positive, and that thyratron will fire a little earlier than it does when the error is zero. In the other thyratron, the grid swings in the negative direction when the anode swings positive, and that thyratron will fire later than it does when the error is zero, or will not fire at all. The result is that the torque output of the d-c motor is proportional to the error signal, for small error signals, and assumes a constant value for large error signals. The direction of the torque is reversed when the sign of the error, and therefore the phase of the error signal, is reversed. It is possible to make the system operate more smoothly by adding a capacitor from each end of the split field to the free end of the armature, but this will slow the response of the system and will require increased damping as compensation. It is possible to use vacuum tubes in place of the thyratrons, but the voltage drop across the tubes will be larger and more power will be required for the same torque output.

55. Vacuum-Tube Control

A vacuum-tube amplifier (fig. 48) can be used to control an a-c induction motor. One field winding is connected to the a-c line, and the other is connected to the output of the amplifier. This method frequently is used when the a-c error signal is of the same frequency as the signal used to drive the motor. It is necessary only to insure that the amplifier output and the line voltage are 90° apart in phase. This system is limited by the power output available from small vacuum tubes. For motors requiring up to 80 watts or so on the control field, the system is efficient and normally is used.

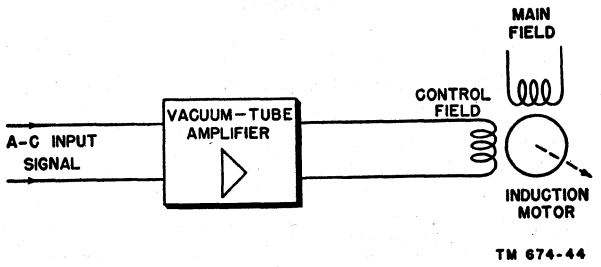


Figure 48. Vacuum-tube control circuit for a-c motor.

56. Saturable-Reactor Control

A saturable reactor is, in effect, an inductor whose inductance can be varied by means of a control current. A saturable reactor properly connected can be used as part of the control system for an a-c motor. The power-handling capability of a saturable-reactor system is far greater than that of a vacuum-tube amplifier, and therefore saturable reactors often are used to control large a-c motors.

a. Saturable-Reactor Theory. When current flows through the windings of an iron-core inductor, a magnetizing force, H, is developed. This, in turn, sets up a magnetic field, G, in the core. When the current is changed, the accompanying change in H causes a change in G, and the change in G induces voltage in all of the windings that

encircle the iron core. The induced voltage is, of course, proportional to the rate at which G changes, and if G is proportional to H, the induced voltage is proportional to the rate at which the current changes. In some types of core material, the relation between G and H is like that shown in A of figure 49. A winding on such a core will show induced voltage when a-c is passed through it. If, now, d-c is added in the same winding or in another, as shown in B, the variation in H no longer takes place about an average value of zero. Instead, H oscillates about a value which corresponds to the d-c current. If this point is sufficiently far beyond the bend in the G–H curve, there will be only a small change in G and a small induced voltage. The result is that an inductor made of such material can be designed to have a high inductance when no d-c flows in the windings, and a much lower inductance when it does flow.

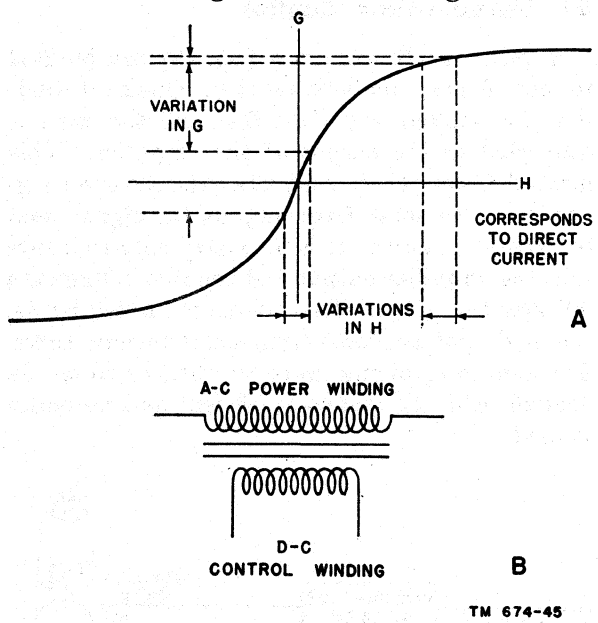


Figure 49. G–H curve for saturable reactor.

b. Saturable-Reactor Control Theory. Figure 50 shows a pair of saturable reactors connected to control an a-c induction motor. The main field of the motor is connected to the line in the usual way. One end of the control field is connected to the center tap of a transformer fed by the line; the other end is connected through a pair of saturable reactors to both ends of the transformer. When no d-c flows through either reactor, the control field is not energized. When d-c flows through either reactor, its inductance is decreased so that the control field is connected to one end of the transformer through a high impedance, and to the other end through a low impedance. It is, therefore, ener-

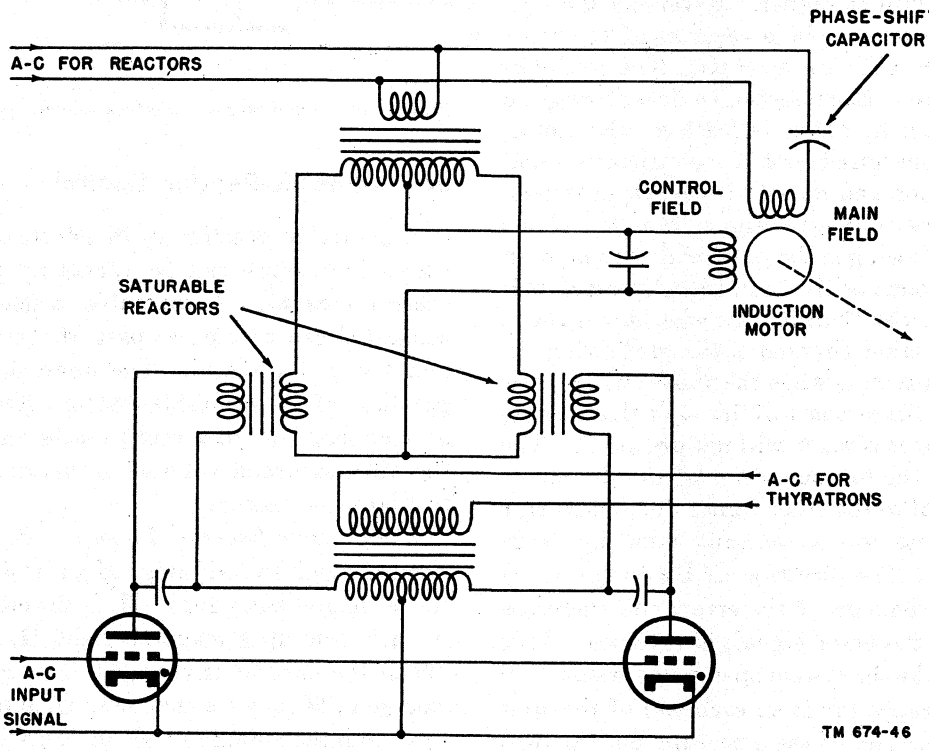


Figure 50. Saturable-reactor control circuit for a-c motor.

gized in one direction or the other, and forward or reverse torque is developed by the motor. The d-c through the reactors is supplied by a pair of thyratrons. These thyratrons receive an a-c error voltage and are connected to an a-c plate supply. Operation of the thyratrons is the same as in the thyratron control circuit discussed above. Note that the a-c for the motor and the reactors may be of one frequency, and the error voltage and the thyratron anode supply may be of another. Vacuum tubes may be used instead of thyratrons if the error signal is a-c. If the error signal is d-c, it may be possible to use it directly to saturate the reactors, or a d-c amplifier may be required.

57. Magnetic Amplifiers

A magnetic amplifier uses saturable reactors (fig. 51) which have extra windings carrying a direct current called the bias current. Figure 52 shows a magnetic-amplifier circuit controlling an a-c motor. It is nearly the same as the circuit for saturable-reactor control (fig. 50) except that the two reactors have their control windings connected in series. The direction in which the bias current flows is so chosen that the magnetizing force developed by the bias current aids the force developed by the control current in one reactor and bucks it in the other. In the absence of a control signal, the direct currents are the same in each reactor and the control field of the motor is not energized. The control current and the bias current are, in effect, added in one reactor and subtracted in the other. Thus, both reactors are partially saturated to begin with, and the control current saturates one further and reduces the saturation of the other. A d-c control signal is required, but this can be obtained from an a-c error signal by means of a phase-sensitive detector, a device described in paragraph 61. Both the magnetic amplifier and the saturable reactor suffer from the fact that, because of the control-winding inductance, it takes a perceptible time to establish the control current. In applications where this time lag is not objectionable, a magnetic amplifier is desirable because it has neither moving parts nor tubes.

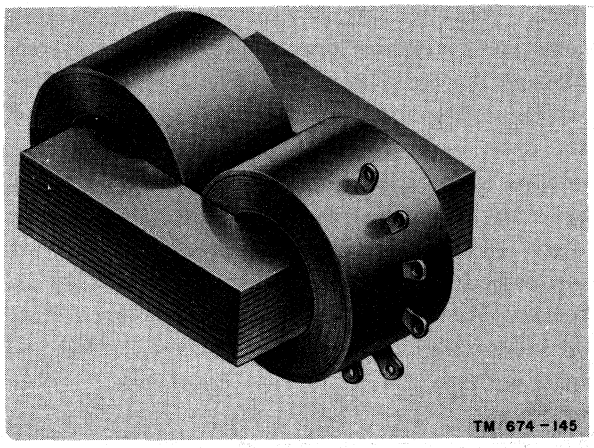


Figure 51. Saturable reactor.

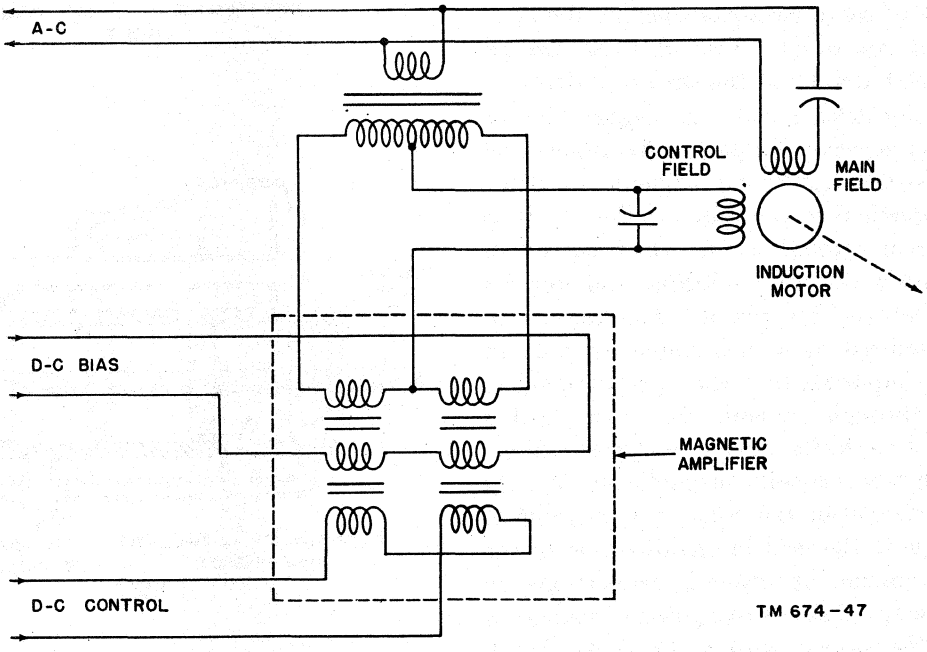


Figure 52. Magnetic-amplifier control circuit for a-c motors.

58. Hydraulic Controllers

The usual hydraulic controller is a valve, which may be operated by a solenoid or by a small motor. Frequently, an auxiliary servo is used to control the hydraulic valve of a main servo. Figure 53 shows a standard valve, which is operated by sliding the shaft back and forth. In the central position, both lines to the hydraulic actuator are cut off. Moving the valve one way or the other connects one of the actuator lines to the high-pressure oil line. The other actuator line then is connected to the low-pressure oil line. So long as the actuator does not move, full pressure is developed in the line leading to the actuator when the valve is open. Actuator motion causes a flow of oil and a consequent pressure drop because of the narrow passage through the valve. For a given oil flow, which corresponds to some fixed actuator speed, the drop in pressure is reduced as the valve is opened wider. This is the basis for the torque-speed relation in a swash-plate motor, or the force-speed relation in a hydraulic ram. The stall torque or force is the same for any valve position, but the torque or force falls off with speed, falling off less rapidly as the valve is opened farther and reaching zero at a higher no-load speed.

59. Combined Actuator Controllers

A number of servo elements combine the actuator and the controller. Two of these are the magnetic-clutch drive and the steel-tape drive.

a. Magnetic-Clutch Drive. A magnetic clutch (A of fig. 54) consists of a pair of flat plates running in a slush of oil, and some magnetic substance. When a magnetic field is applied to the clutch by passing current through a coil which surrounds the oil chamber, the slush solidifies and forms a connection between the plates. The amount of torque transmitted by such a clutch for a given speed of the input shaft is then proportional to the current through the coil. In B, the load is connected to two shafts moving in opposite directions, in each case through a magnetic clutch. By energizing one coil or the other, it is possible to deliver torque to the load in one direction or the other. The amount of torque is proportional to the coil current. C shows one possible method of controlling the system with a d-c error signal.

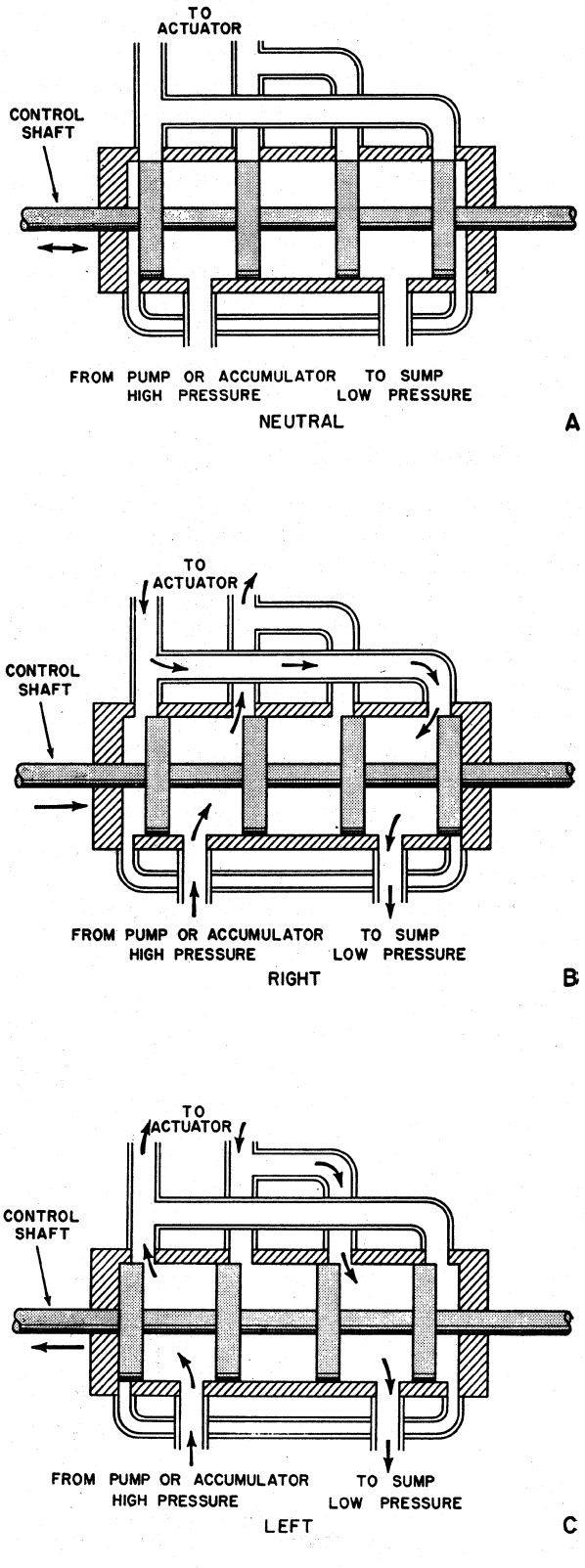


Figure 53. Hydraulic valve.

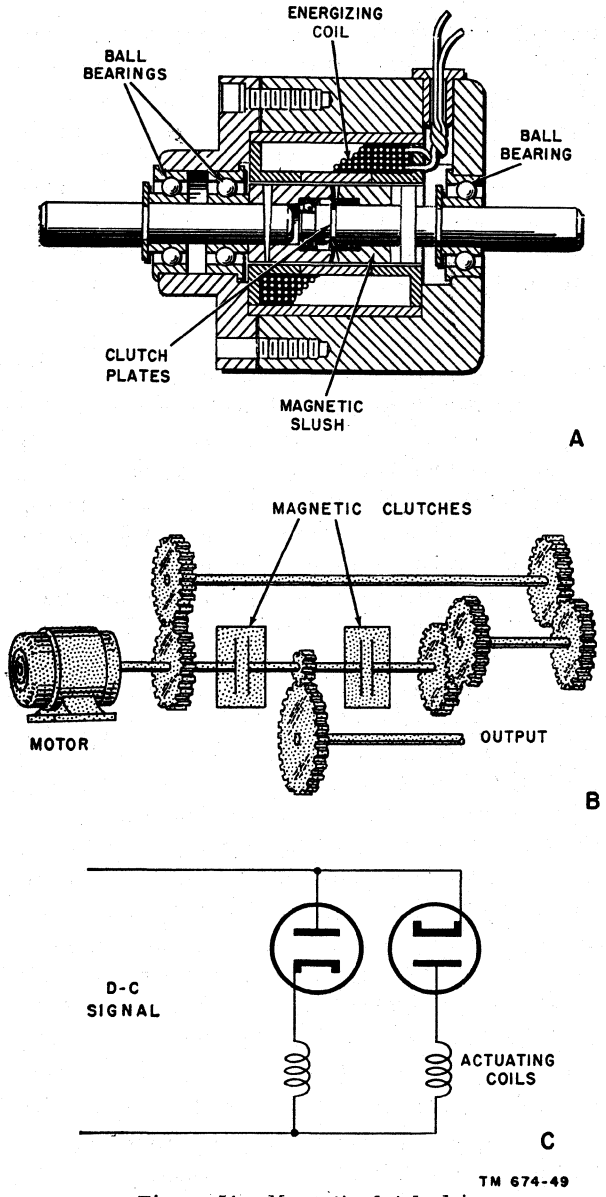


Figure 54. Magnetic-clutch drive.

Each coil is in series with a rectifier. One rectifier conducts for positive error signals, the other for negative error signals.

b. Steel-Tape Drive. Another useful combination of actuator and controller is the steel-tape drive shown in figure 55. It consists of a single drum connected to the load through gears and shafts, and two driving drums turned at constant speed by a motor. Two steel tapes connect the load drum to the two driving drums, which turn in opposite directions. Control bars press on one or the other of the steel tapes and a gentle force exerted by a control bar can develop a tremendous tape tension. When this happens, the tape is dragged along by the driving drum and pulls the load drum around with it. Control of the load is, therefore, accomplished by pressing on one tape or the other with the appropriate control bar.

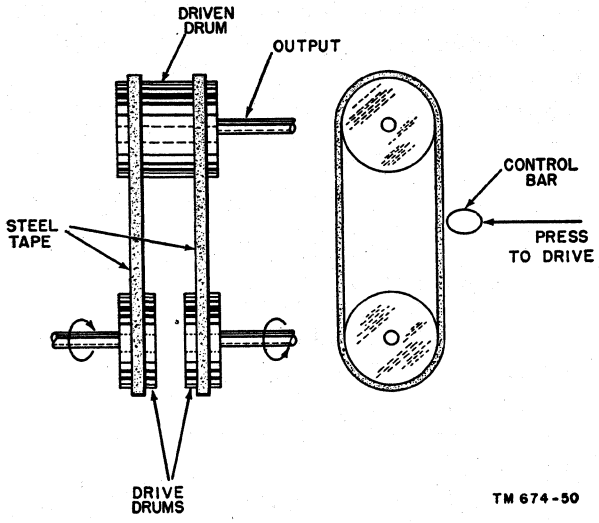


Figure 55. Steel-tape drive.

Section III. AUXILIARY ELEMENTS PRECEDING CONTROLLER

60. Modulators

Electrical signals in a servo system may be either a-c or d-c. In a-c, a signal of some specified phase is considered positive, and one differing from this by 180° is considered negative. With d-c signals, one polarity is considered positive and the other negative. Since some servo components may require d-c and others in the same system may require a-c, it is desirable to have devices which can convert electrical signals from d-c to a-c, or vice versa. A modulator is a device which converts a polarized d-c signal to a properly phased a-c signal. There are several types of modulators, including the mechanical and vacuum-tube choppers and the rectifier modulator.

a. Mechanical Chopper. The mechanical chopper (fig. 56) is simply a synchronized switch. Its output line is connected alternately to its input line and to ground, or zero-level d-c. The coil is energized by a-c of the appropriate frequency. In

order to prevent the vibrating arm from being attracted by the coil twice during each cycle, some direct current is passed through the coil, or through another coil on the same core. Thus, when the a-c flows in one direction, its magnetizing force is aided by that of the d-c and the vibrating arm is attracted, but when the a-c flows in the other direction, its magnetizing force is canceled by that of the d-c, and the attraction on the arm is reduced. The arm thus vibrates at the frequency of the a-c. To reduce the power required to drive the arm, it is usual to tune it so that it vibrates naturally at the proper frequency. The output is then a square wave, having the level of the d-c input for one half-cycle and having zero level for the other. Blocking condensers in the following amplifier remove the d-c component, so that the signal becomes a square wave with an amplitude proportional to the d-c signal level and a phase which reverses when the d-c signal changes polarity. The following amplifier also discriminates against high-frequency signals, so that the square wave ultimately is converted to a sine wave at the frequency of the chopper switching.

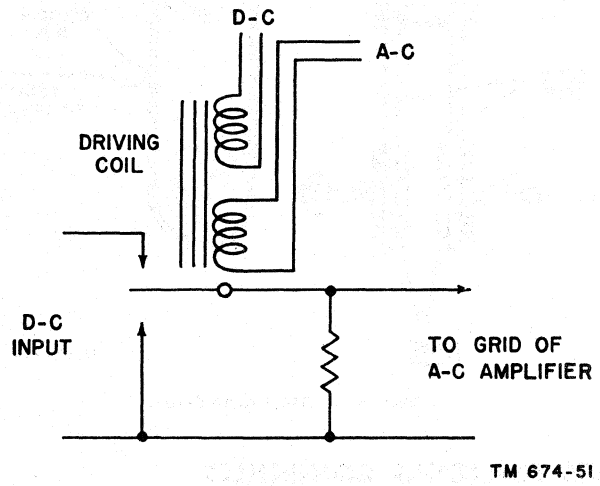


Figure 56. Mechanical-chopper circuit.

b. Vacuum-Tube Chopper. The vacuum-tube chopper circuit (fig. 57) consists of two tubes, one having a pulsed d-c signal on its control grid, and the other a fixed voltage. Alternating current at the proper frequency is applied to the screen grids, the voltages at the two screen grids being 180° out of phase with each other. When the tubes carry the same current, the effect of raising one screen is exactly balanced by that of lowering the other screen; consequently, the total current flowing in the common load resistor is unchanged, and there is no a-c output. In the presence of a d-c signal, this is no longer true; a-c will appear across the load resistor with an amplitude proportional to the d-c level and a phase which reverses when the d-c polarity is changed. The variable cathode resistor in one tube is used to balance the currents so that the output drops to zero when the input is zero. There are many other ways in which vacuum tubes can be employed to arrive at the same result.

c. Rectifier Modulator. The rectifier modulator (fig. 58) is another type of synchronous switch. During one half-cycle, an a-c reference signal causes current to flow through D1 and D2; during the other half-cycle, it flows through D3 and D4. The nonconducting diodes look like open circuits, and the conducting diodes look like relatively low resistances. One end of the input resistance is, therefore, connected to the center tap of a divider across the output of the reference a-c transformer, and is at the same voltage as the center tap on the transformer secondary. The output voltage, then, is equal to that appearing across one half of the input resistor. Because of the switching action, the output circuit sees the voltage across upper and lower halves of the input resistor alternately, measuring both voltages in respect to the center of the resistor. The resulting output voltage is equal to half of the input voltage during one half of the a-c cycle, and the negative of this during the other half of the a-c cycle; the action is the same as that of a mechanical chopper (*a*, above). Since one side of the input resistor usually is grounded, it is necessary to take the output through an isolating transformer in order to remove the d-c component.

61. Commutator

A commutator, sometimes known as a phase-sensitive detector, makes the same conversion as a modulator, but in the reverse direction. It receives an a-c input, and develops a d-c output. For an input of one phase, it develops a positive output. For an input with a phase 180° different, it develops a negative output. For inputs differing from these by 90°, it develops no d-c output. There are several types of commutators, including the synchronous mechanical switch, and vacuum-tube and rectifier commutators.

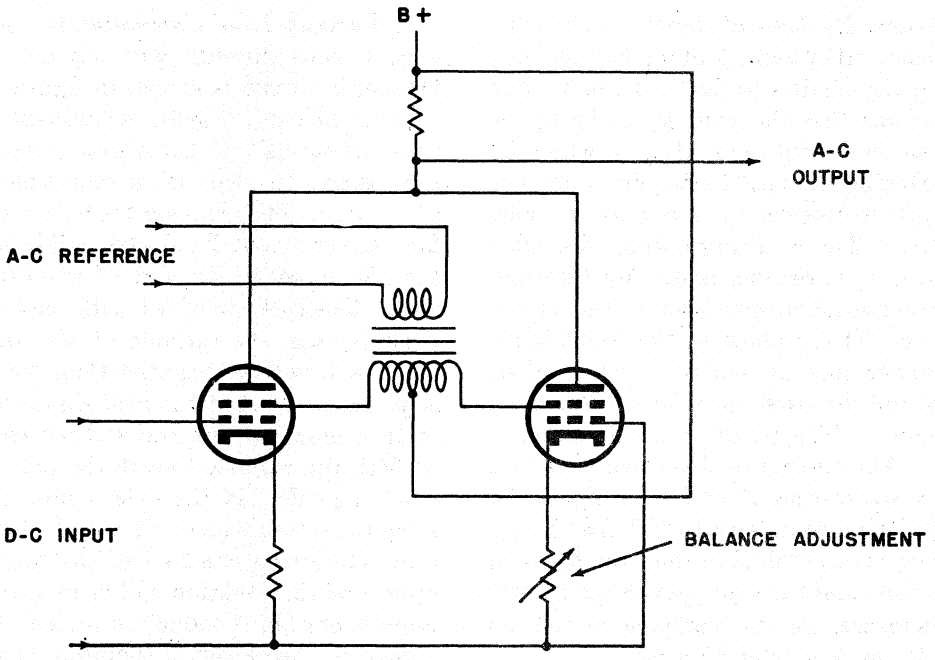


Figure 57. Vacuum-tube chopper circuit.

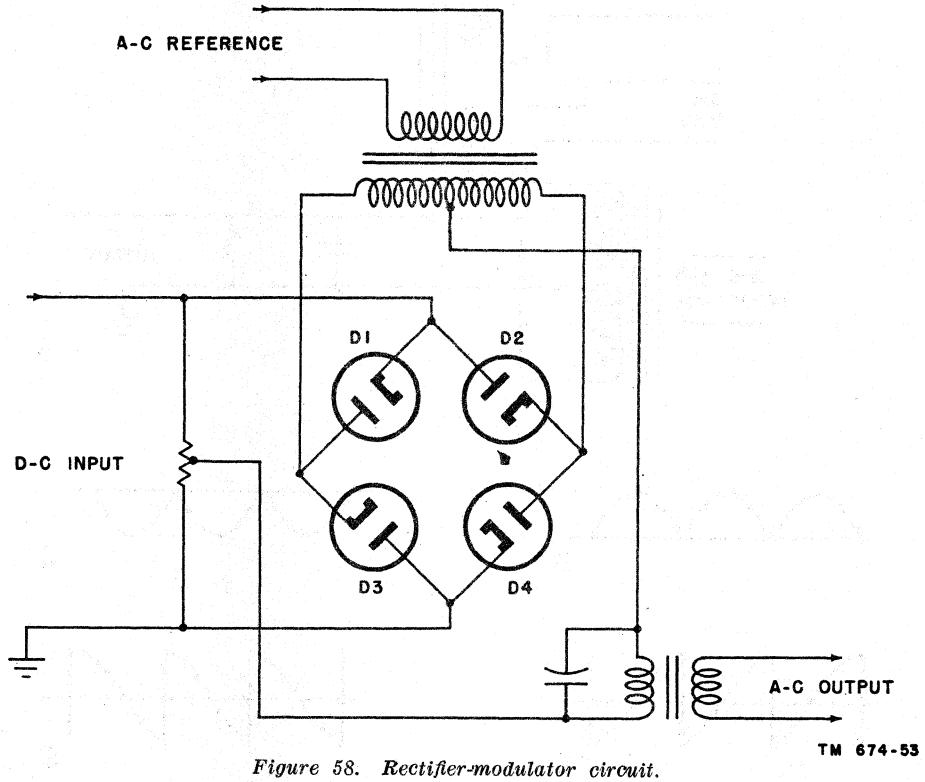


Figure 58. Rectifier-modulator circuit.

a. Synchronous Mechanical Switch. The synchronous mechanical switch (A of fig. 59) depends on a vibrating arm similar to that of a mechanical chopper. Assume that the voltage at the upper contact is positive during the half-cycle when the arm is up. During the next half-cycle, when the arm is down, the voltage at the lower contact also will be positive. The resulting output is similar to that of a full-wave rectifier and, after filtering, it has a d-c component proportional to the amplitude of the a-c. If the phase of the input is reversed, the upper contact will be negative when the arm is up, and the lower contact negative when the arm is down. The result, after filtering, is negative d-c. The signals in these two examples are shown by waveforms B and C in figure 59. For signals differing from these by 90°, the voltage at each contact reverses during the time the arm makes connection, and the average voltage is zero. There is, therefore, no d-c component and no output from the system after filtering.

b. Vacuum-Tube Commutators. A number of vacuum-tube circuits will act as commutators. One such circuit is shown in figure 60. The d-c bias on the control grids is sufficient to hold both tubes at cut-off. Assume that the grids move in the positive direction at the same time as the screen of V1, figure 60. During the half-cycle of current flow, the screen of V1 always will be more positive than the screen of V2, and V1 will draw more current. The cathode of V1 will, therefore, be more positive than the cathode of V2, and the anode of V1 will be more negative than the anode of V2. A phase reversal of the grid signal will cause V2 to draw more current, and will reverse the polarity of both the cathode-to-cathode and the anode-to-anode signals. If the grid signal differs by 90° from the screen signal, V1 will draw more current than V2 during one half of the conducting half-cycle, and the situation will be reversed during the remainder of the conducting period. The d-c component of the output is therefore zero. A circuit

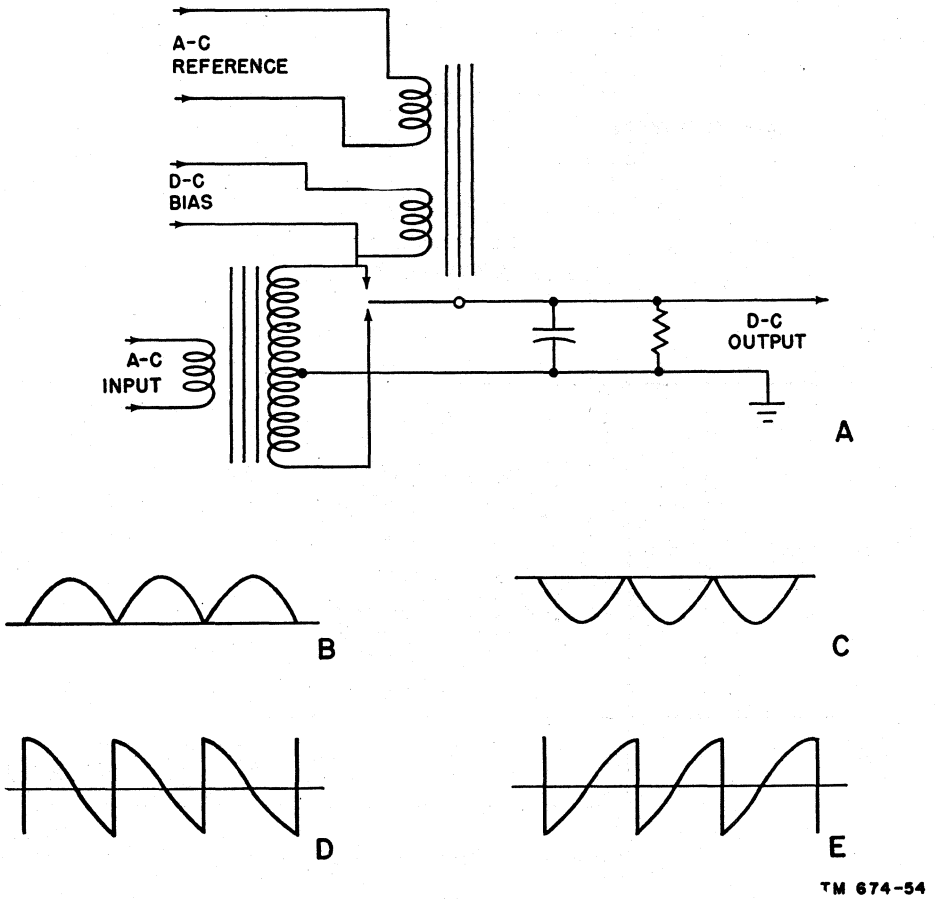


Figure 59. Synchronous-switch circuit and output waveforms.

of this sort is useful where d-c output need not be developed in respect to ground as, for example, in controlling the field current of a Ward-Leonard or amplidyne drive.

c. Rectifier Commutator. A rectifier commutator (fig. 61) acts in much the same way as the rectifier modulator (par. 60*c*). During one half-cycle, the reference a-c causes D1 and D2, figure 61, to conduct; during the other half-cycle, it causes D3 and D4 to conduct. The output circuit thus is connected alternately from the center tap of the input transformer to the junction of the upper diodes and from the center tap to the junction of the lower diodes. The results are the same as in the case of the synchronous mechanical switch (*a*, above).

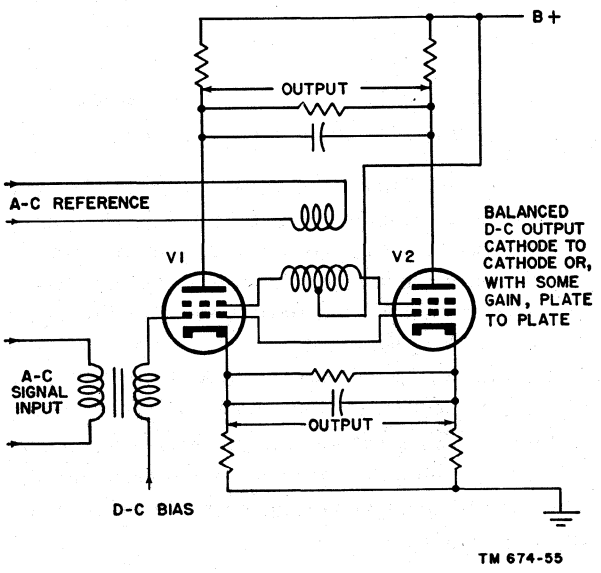


Figure 60. Vacuum-type commutator circuit.

62. Variable-Gain Amplifier

In many applications, an amplifier whose gain can be controlled by an electrical signal is desirable. One example of this sort of amplifier is the variable-gain amplifier shown in figure 62. The control signal is amplified in pentode V2 and amplified further in the amplifier circuits. The resulting signal is referred to some positive d-c level and then rectified in V3, negative-peak rectifier. Signals below some threshold level produce no output from the rectifier. Signals above the threshold level develop a negative d-c which is filtered and used to bias the pentode. In the presence of a control signal, the pentode is biased negatively until the rectifier output is only large enough to supply the required bias. Roughly speaking, doubling the control signal will halve the gain of the pentode. The same bias is used to vary the gain of pentode V1 which carries the

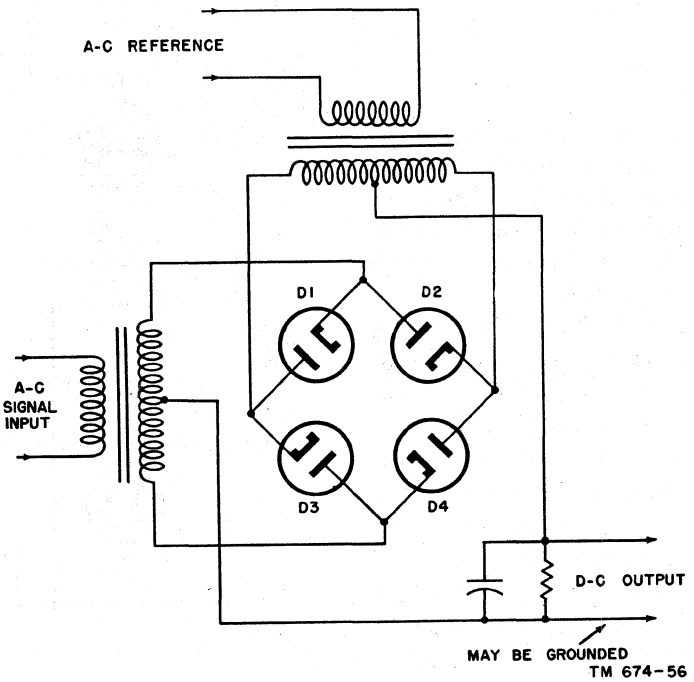


Figure 61. Rectifier-commutator circuit.

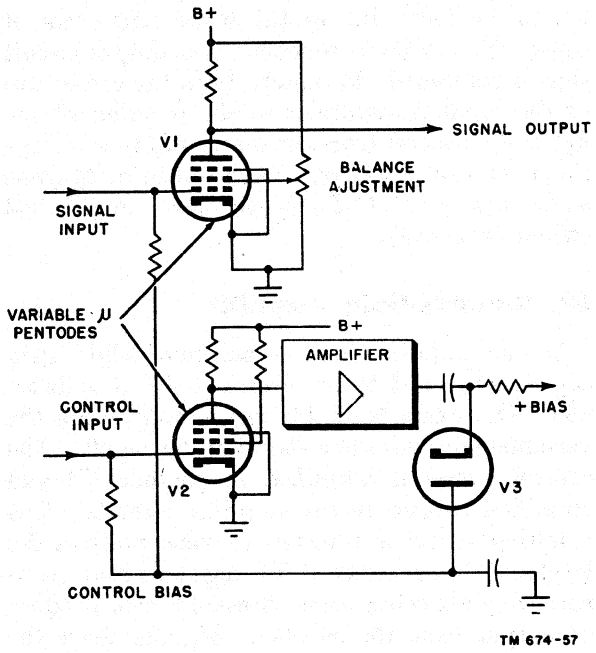


Figure 62. Variable-gain amplifier circuit.

signal. Variable screen voltage on V1 allows the cut-off points to be matched so that the gains of the two pentodes will be matched reasonably over a range of bias. The result is that the gain through the signal channel is inversely proportional to the level of the control signal over a reasonable range of levels.

63. Transfer Circuits

Transfer circuits are mentioned in paragraph 20 as necessary for operation with coarse-fine systems to transfer control of the servo from the coarse sensing element to the fine sensing element. This can be accomplished by means of relay, vacuum-tube, or rectifier circuits.

a. Relay Transfer Circuit. The relay transfer circuit (fig. 63) is the simplest of all such circuits. It consists of a relay which is energized by the coarse error signal. When the signal is large, the relay pulls in and the servo is controlled by the coarse error signal. When the coarse signal is small, the relay drops out and control is transferred to the fine error signal. The chief disadvantage of the relay system is that it may not transfer rapidly enough for a high-performance servo. For this reason, vacuum-tube and rectifier circuits are used more frequently.

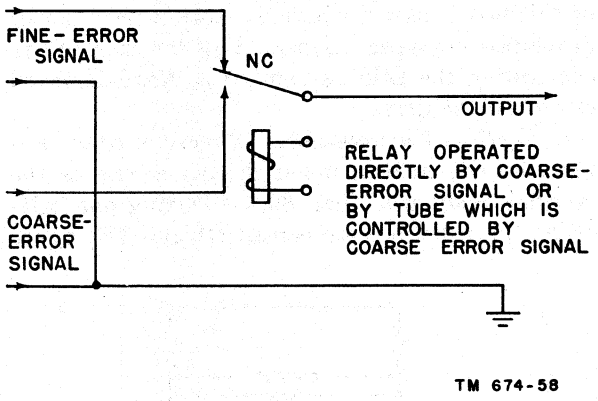

FINE-ERROR SIGNAL
NC
OUTPUT
RELAY OPERATED DIRECTLY BY COARSE-ERROR SIGNAL OR BY TUBE WHICH IS CONTROLLED BY COARSE ERROR SIGNAL
COARSE-ERROR SIGNAL
TM 674-58

Figure 63. Relay transfer circuit.

b. Vacuum-Tube Transfer Circuit. In the vacuum-tube transfer circuit (fig. 64), the biases of the tubes are adjusted, by means of the cathode resistors and the bleeders from high voltage to the cathodes, so that V1 normally passes the fine error signal, whereas V2 is cut off and does not pass the coarse signal. The coarse signal is rectified by V3 and V4 which develop positive and negative voltages. The positive voltage shifts the bias on V2 and causes it to pass the coarse error signal, whereas the negative voltage shifts the bias on V1 and cuts it off.

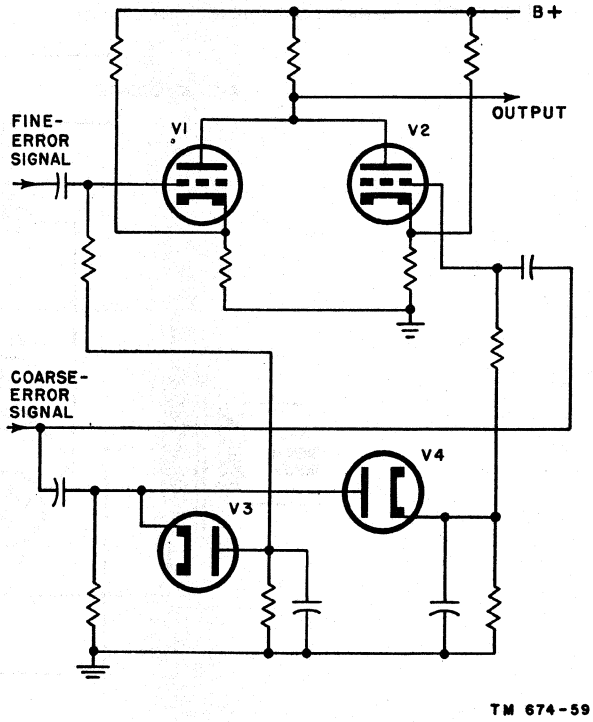


Figure 64. Vacuum-tube transfer circuit.

c. Rectifier Transfer Circuit. The rectifier transfer circuit (A of fig. 65), depends on the nonlinearity of the rectifiers. Each of the rectifiers looks like an open circuit in the nonconducting direction. In the conducting direction, it looks like a high resistance for small signals and like a lower resistance for larger signals. Both coarse and fine signals are developed across voltage dividers which include rectifiers. Because of the connection, little of the coarse signal appears at the output of the circuit until a certain minimum level has been reached. Thereafter, most of the coarse signal is passed. The fine signal is passed without attenuation so long as it is small but, as it grows, it is limited by the diodes (B of fig. 65). The over-all result, after the signals are added, is that the output follows the fine error signal only when it is small, and the coarse error signal only when it is large. The levels are so chosen that the coarse signal, when it is large, will always override the fine signal.

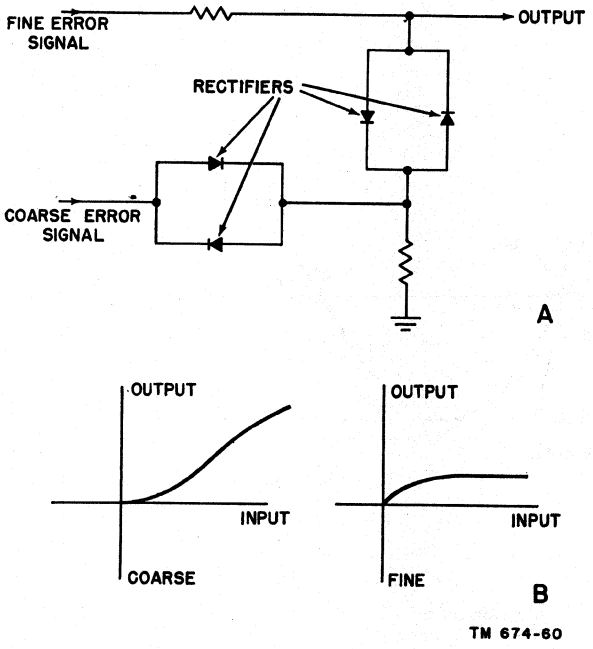


Figure 65. Rectifier transfer circuit.

d. Bias Requirement With Transfer Circuits. In most systems where the follow-up head and data-transmission head make more than one revolution, there are two positions of the sensing element for which it delivers a zero output. This will be true, for example, with the contact sensing element described in paragraph 14*a* and figure 8, if the two fixed arms are replaced by segments so that complete revolution is possible. Although there is no error voltage at either of these positions (which are called nulls), only one of them is stable, since the servo will drive toward one and away from the other (A of fig. 66). The two nulls are usually 180° apart, and this raises a difficulty in the case of a coarse-fine system having an even ratio. Assume, for example, that the fine system makes 36 revolutions for one revolution of the coarse system. The proper load position is one for which both fine and coarse sensing elements are at stable nulls. For other positions nearby, the fine sensing element will provide an error signal that causes the servo to drive the load in the proper direction; for positions more distant from the proper position, the coarse sensing element will provide such a signal. Suppose, however, that the load is displaced just far enough to shift the coarse follow-up head by 180°. The coarse sensing element then will be at a null and will relinquish control to the fine sensing element. With a coarse-fine ratio of 36, a half-revolution of the coarse system is accompanied by 18 turns of the fine system, and the fine sensing element will be at a stable null. The servo now will hold the load at this position unless, through some circumstances, the error grows large enough to transfer control to the coarse sensing element. If this happens, the load will be driven to the proper position. However, if the servo positions the load with accuracy, the error may never grow that large. This cannot happen if the coarse-fine ratio is odd—27, for example—for the fine sensing element then will have turned through a number of complete revolutions and an odd half-turn—13½ turns if the ratio is 27—and the point in question will be an unstable null for both coarse and fine systems. The situation is remedied by displacing the unstable null of the coarse sensing element so that it coincides with an unstable null of the fine element (B of fig. 66). With a coarse-fine ratio of 36, the unstable null of the coarse element may be shifted by 5°, and moving the coarse element from one null to the other null will turn the fine sensing element through 17½ or 18½ turns. If a synchro, which is described later in this chapter (par. 72) is used for a sensing element, the error signal it develops is proportional to the sine of the error angle. The two nulls thus are always 180° apart, and it is not desirable to modify the synchro. The solution is to add a small voltage to the output of the synchro

and then to use the sum of the two as an error signal, as in C of figure 66. Suppose that the voltage added is equal to the output of the synchro for a positive error of 2.5°. The resulting error signal will vanish when the actual error is minus 2.5° and also, because of the synchro characteristic (output proportional to the sine of the error), at an error of minus 177.5°. The synchro may now be offset by 2.5°. At the stable position, the actual error is zero. The synchro then sees an error of minus 2.5°, and its output is equal and opposite to the bias signal, so that the resulting error signal is zero. Because of the offset, the synchro sees an error of minus 177.5° when the actual error is only minus 175°. At this point, also, its output balances the bias voltage to give a zero error signal. The stable null is then at zero, but the unstable null has been shifted by 5° to minus 175°, where it coincides with an unstable null of the 36-speed fine synchro.

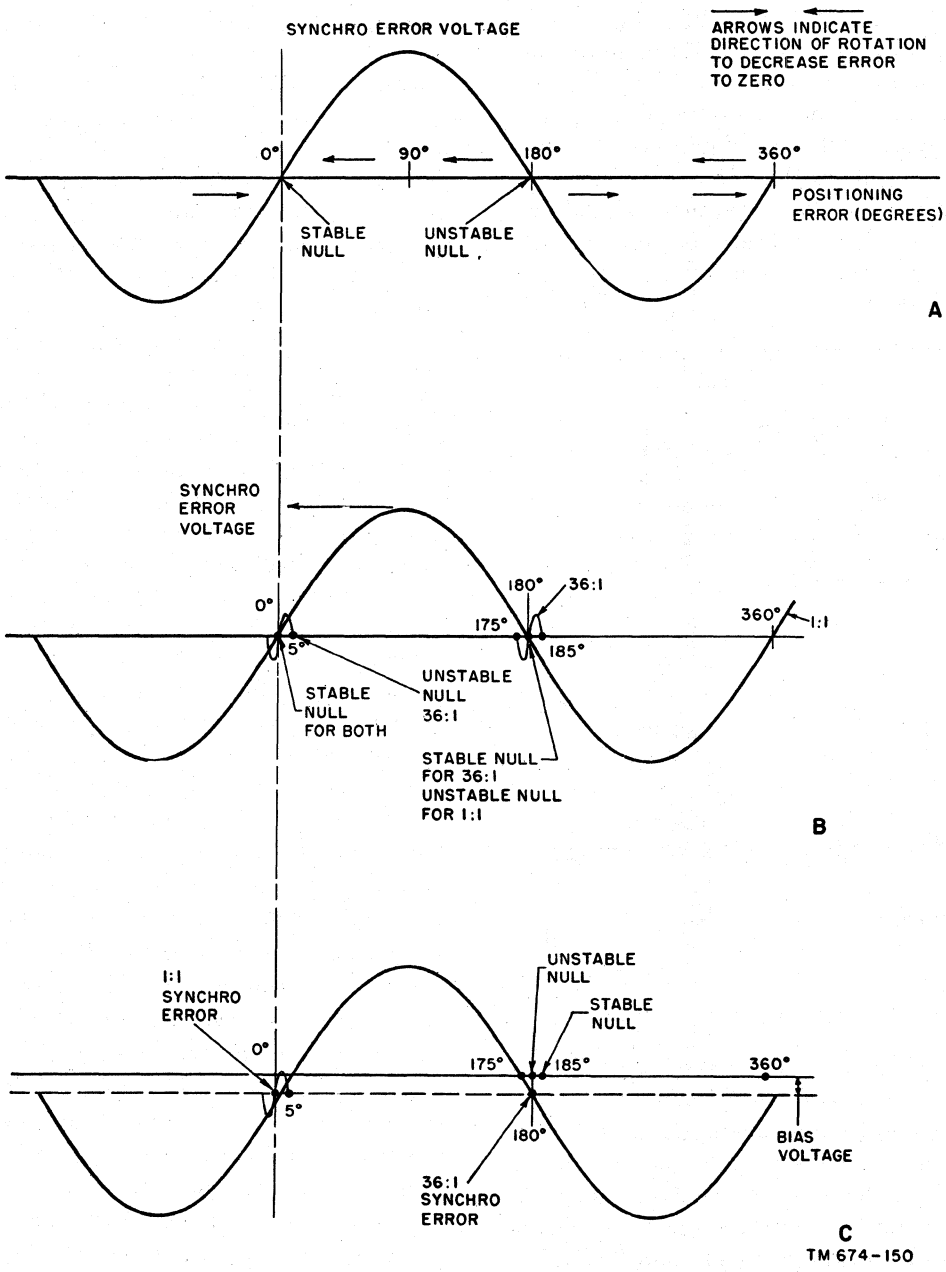


Figure 66. Phase-error positioning.

64. Damping Networks

Damping networks are circuits which develop outputs having two components; one component is proportional to the input, and the other is proportional to the derivative of the input or to the rate at which it varies. Such networks are used to develop the signals required for error-rate damping. Some damping is obtained from mechanical friction, and a small amount is present because of the torque-speed characteristics of most actuators. Friction, however, varies from time to time, and it is therefore undesirable to depend on it for critical damping. Usually, the damping available from actuator characteristics is only a negligible fraction of that required. Additional damping may be obtained from a tachometer generator if the accompanying velocity lag can be tolerated, but in most high-performance servos error-rate damping, developed by a damping network, is used.

a. D-C Damping Network. The d-c damping network shown in figure 67 consists of a series impedance and a shunt impedance. The series impedance is a high resistance, so that the major portion of the total voltage drop appears across it and the resulting current flow through the network is then proportional to the input voltage. The shunt impedance consists of a resistance in series with an inductance. The voltage across the resistance is proportional to the current flowing through it and therefore is proportional to the input voltage presented to the network. The voltage across the inductance is proportional to the rate at which the current varies and so is proportional to the rate at which the input voltage varies. If the input signal is a voltage proportional to the error, the voltage across the shunt resistor will be proportional to the error, and the voltage across the inductor will be proportional to the error rate. These are the positioning and damping voltages, and their sum is the error signal which is sent to the controller. The behavior of this circuit can be described in terms of its response to signals of different frequencies, and almost any circuit having the same frequency-response characteristic will serve also as a damping network. For direct current and at low frequencies, the reactance of the inductor is negligible, and the network behaves like a voltage divider consisting only of the two resistors. At some frequency, the reactance of the inductor will equal the resistance of the shunt resistor. Above this frequency, since reactance increases with frequency, the shunt resistor may be neglected. The network then looks like a divider consisting of the series resistor and the inductor, and the ratio of output to input rises with increasing frequency as the reactance increases. At some still higher frequency, the reactance is equal to the series resistance, and above that frequency, the network has negligible attenuation. A network having similar behavior, which also may be used for damping, consists of a resistor as the shunt impedance, and a resistor paralleled by a capacitor for the series impedance. This network provides damping only as long as the major portion of the input voltage appears across the series resistor. For sufficiently high error rates, however, this will not be true. The range may be extended by increasing the value of the series resistor and accepting a lower output level.

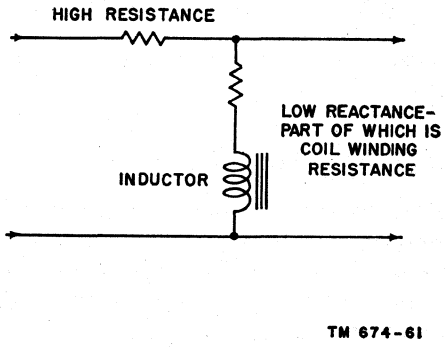


Figure 67. D-c damping network.

b. A-C Damping Network. Damping is obtained for a d-c error signal by the use of a network having the frequency response described in *a* above. In an a-c error signal, a frequency response of the same sort also will provide damping, but the signal frequency takes the place of the zero frequency of a d-c signal (B of fig. 68). Thus, if the d-c damping network has a certain response at 10 cycles, the a-c network must have the same response at 10 cycles above the signal frequency, and also at 10 cycles below. The frequency response of the d-c damping network and that required of an a-c network are shown in A of figure 68. A circuit having the required response is illustrated in B. A 10-cycle signal in the d-c network appears as 10-cycle modulation of the d-c, whereas, in the a-c network, it appears as 10-cycle modulation and develops two side

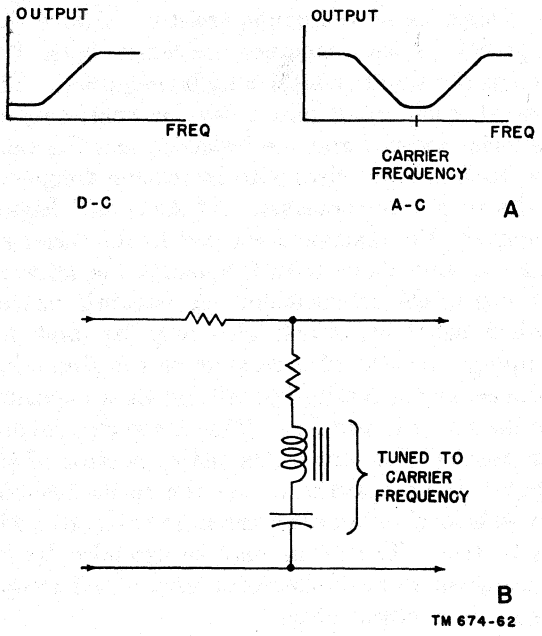


Figure 68. A-c damping network.

bands spaced 10 cycles above and below the a-c frequency.

65. Integrating Networks

The requirements for an integrating network are explained in paragraph 41. There are both a-c and d-c networks. With inputs proportional to the error, they deliver outputs proportional to the error plus the integral of the error.

a. D-C Integrating Network. A d-c integrating network (fig. 69) consists of a series impedance and a shunt impedance. The series impedance is a high resistance, so that the current flow is proportional to the input voltage. The voltage across the shunt resistor is proportional to the current and therefore is proportional to the input voltage. The voltage across the capacitor is proportional to the charge on it. Since the average charging current is proportional to the average input voltage, the total charge is proportional to the average of the input voltage multiplied by the length of time the input voltage has persisted. This is precisely the integral of the input voltage. The network therefore supplies a voltage that is the sum of two components—one proportional to the input voltage, the other proportional to the integral of the input voltage. For d-c, the circuit does not attenuate, since the reactance of the capacitor is infinite. At some frequency, the reactance will be equal to the series resistance. Above that frequency, the response drops because of the falling reactance. At some higher frequency, the reactance is equal to the shunt resistance, and for frequencies above that the network acts like a simple voltage divider composed of the two resistances. A comparison of this frequency response with that of the damping network shows that an integrating network is antidamping. As before, the characteristics of the circuit do not permit integration if the integral of the error voltage becomes too great. The drop across the capacitor then is no longer negligible in comparison with that across the series resistor, and proper action is no longer obtained.

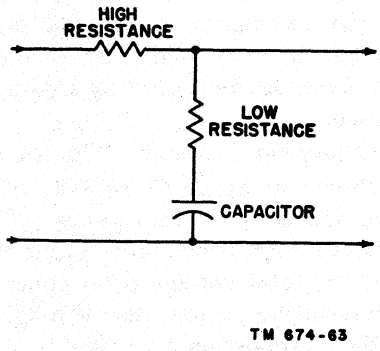


Figure 69. D-c integrating network.

b. A-C Integrating Network. The a-c integrating network (A, fig. 70), can be developed from the d-c integrating network in the same way that the a-c damping network (par. 64*b*) was developed

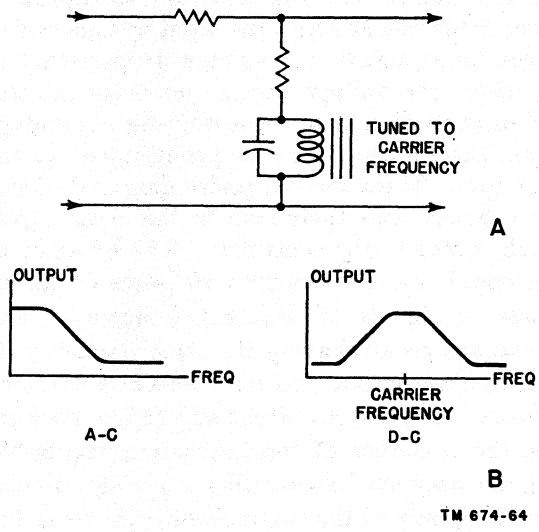


Figure 70. A-c integrating network.

from the corresponding d-c damping network. The two graphs in B, figure 70, show the frequency response of the d-c integrating network and that required of the a-c integrating network. The circuit is one which has the appropriate response.

Section IV. BASIC SENSING ELEMENTS

66. Mechanical Differential

The mechanical differential is the basic sensing element used to compare two mechanical positions when they are in the form of shaft rotations. Its operation can be understood easily from A, figure 71. This shows two racks and a small gear which meshes with both of them. If the two racks move equal distances in the same direction, they will carry the gear with them. If only one rack moves, the gear will roll between the racks and will move half as far as the moving rack. If the racks move equal distances but in opposite directions, the gear will roll between them but remain in the same place. In the mechanical differential, the two racks are folded around on themselves (B of fig. 71) and become a pair of bevel gears. The gear

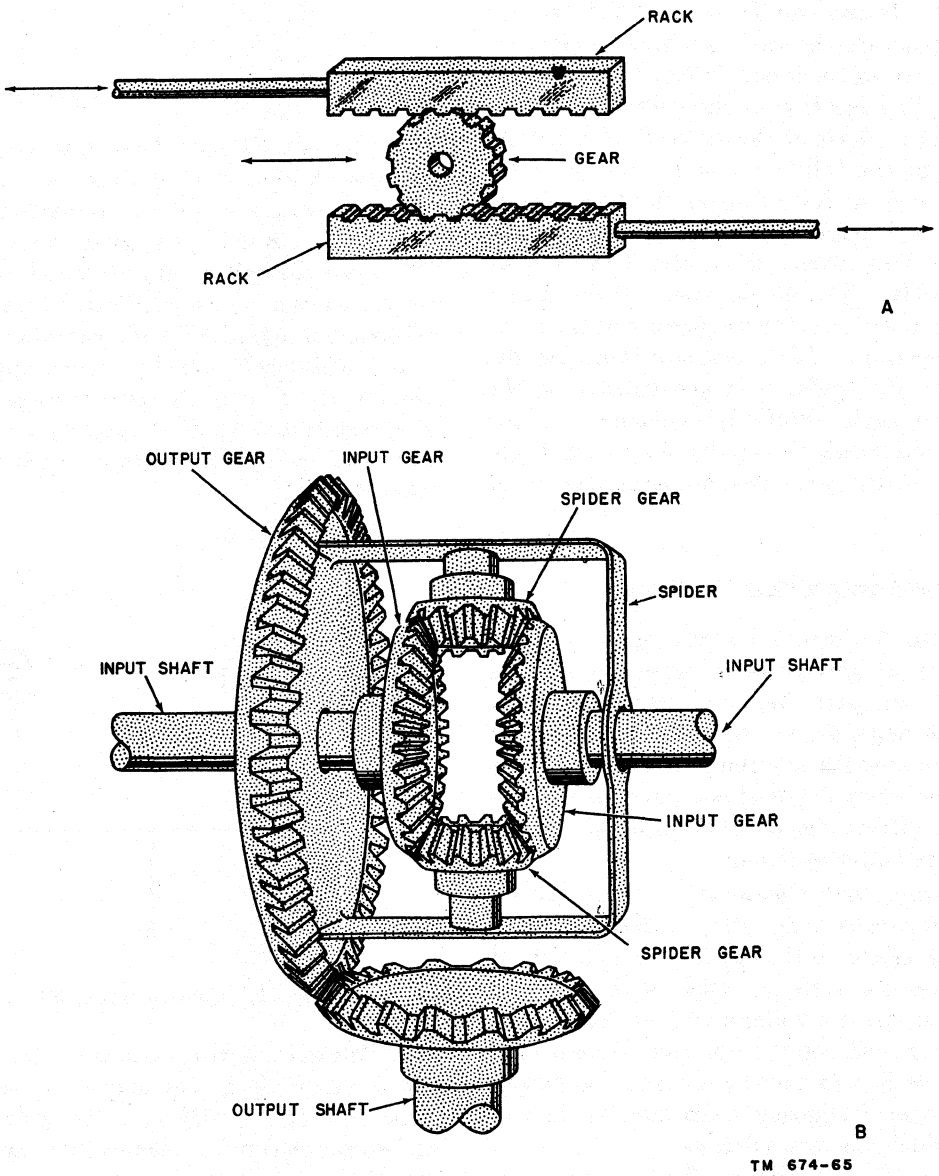


Figure 71. Mechanical differential.

between the racks is replaced by a gear called the spider gear, which is carried on a mounting frame called the spider. In the usual differential, there are two spider gears. If both of the input shafts turn through the same angle in the same direction, the spider will rotate through the same angle. If only one input shaft is turned, the spider will rotate through one-half the angle of that input shaft. If the input shafts are turned through equal angles but in opposite directions, the spider will not move. The behavior of the differential is summed up by the statement that the spider turns through an angle equal to one-half the sum of the angles through which the input shafts have been turned. It now can be seen that the mechanical differential may be used as a sensing element. Assume that one of the input shafts of the differential is turned by rotation of the data-input shaft. The other input shaft of the differential is turned by rotation of the follow-up shaft. If the data-input shaft and the follow-up shaft turn in opposite directions through equal angles, the spider will not rotate. This occurs when the load is positioned properly. The displacement of the spider from its zero position is thus a measure of the error in the load position. If the actuator is mechanical or hydraulic, the spider may act directly on the controller through additional gearing. If the actuator is electrical, the spider may turn a potentiometer which provides an electrical error signal.

67. Voltage-Comparison Methods

Where both the external input signal and the follow-up signal appear as voltages, the sensing element must compare them and develop an error voltage that depends on the difference between them. There are several circuits for this purpose, including the vibrating-reed comparator, the differential amplifier, the parallel-addition circuit, and the series-addition circuit.

a. Vibrating-Reed Comparator. The vibrating-reed comparator (fig. 72), is essentially the same as the mechanical chopper, except that it compares two d-c voltages whereas the chopper compares a single d-c voltage with zero level d-c. The vibrating-reed comparator can be used only where the two inputs may be d-c and the output a-c. The output frequency is the same as the frequency at which the reed vibrates.

b. Differential Amplifier. The differential

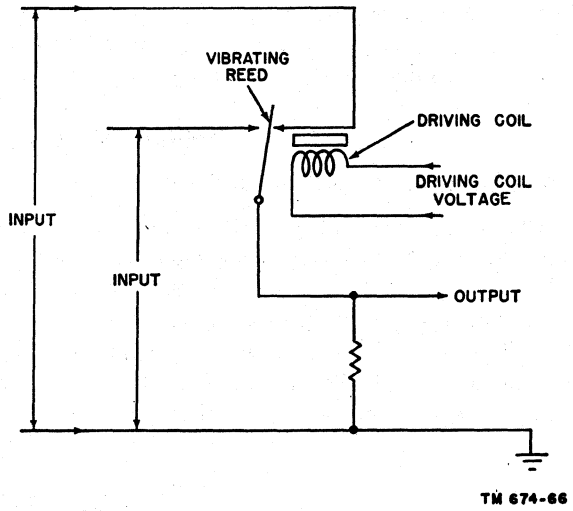


Figure 72. Vibrating-reed comparator circuit.

amplifier (fig. 73) may be used to compare two d-c voltages, and it then delivers a d-c output. It also may compare two a-c voltages, delivering an a-c output. Raising the grid voltage of V1 (fig. 73) causes the voltage at the cathode to rise. Since the cathodes are connected directly, this raises the cathode voltage of V2 and decreases its plate current, which has an effect precisely opposite to that obtained by raising the grid voltage of this tube. The resulting output, at the anode of V2, is proportional to the difference between the two grid signals.

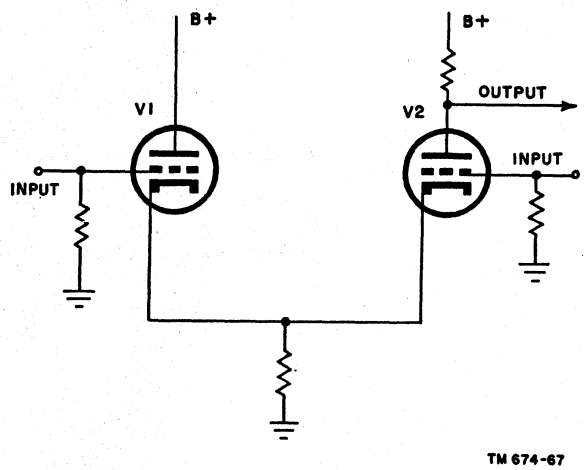


Figure 73. Differential-amplifier circuit.

c. Parallel-Addition Circuit. The parallel-addition circuit (fig. 74) may be used to compare either a-c or d-c voltages. If the several series resistors are equal to each other, and have high resistance compared to the shunt resistor, the cur-

rent through each circuit will be proportional to the applied voltage. All the current flows through the shunt resistor, and the voltage appearing across it therefore is proportional to the sum of the inputs. By making the external input a positive voltage, and the follow-up signal a negative one, the output can be made proportional to the difference between them—that is, proportional to the error. One difficulty with this system is that it operates properly only when the output voltage is small compared with each of the inputs. Another trouble is that one side of each input line must be tied to one side of the output. This normally requires that each of the inputs be developed as a voltage above or below ground. In spite of these objections, the system frequently is used for the addition, or subtraction, of d-c voltages.

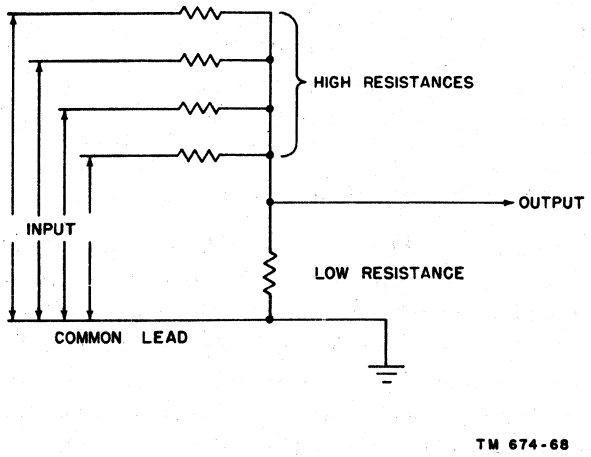


Figure 74. Parallel-addition circuit.

d. Series-Addition Circuit. The series-addition circuit shown in figure 75 is more precise than the parallel-addition circuit described in *c* above and, in addition, delivers the full sum of the voltages instead of a fraction of the sum. It normally is employed for addition of a-c voltages. Because of the transformers it cannot be used with d-c.

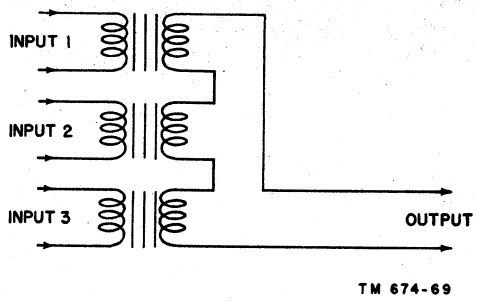


Figure 75. Series-addition circuit.

68. Other Sensing Elements

A number of other sensing elements are in general use. Most of these act as combination sensing elements, data receivers, and follow-ups. For this reason they are considered separately in subsequent sections of this chapter.

Section V. SYNCHROS

69. General

Synchros, or self-synchronous motors, are known by a wide variety of names. The most common of these is Selsyn, the General Electric trade name. Others are Autosyn, Telesyn, and Teletorque, and a number of others that are seen less frequently. The preferred name, however, is *synchro*, which applies to all of the various types described in this section. Synchros are devices which convert mechanical shaft angles to electrical signals and vice versa, their principal use being for data transmission. When information is in the form of a shaft position, so that it is expressed in terms of the angle between the actual shaft position and some zero or reference position, it can be converted by a synchro to a set of three voltages called synchro data. In this form, such information can easily be transmitted to another point, where a second synchro may be used to set a second (repeater) shaft to a corresponding position. In some cases, the second synchro develops torque and is used to set the repeater shaft directly. In other cases, the second synchro controls a servo which sets the repeater shaft. A synchro control transformer is used in this application. The synchro control transformer is one of the more common servo components, and in its usual application serves as data receiver, follow-up, and sensing element.

70. Synchro Transmitter

A synchro transmitter receives a mechanical shaft position and delivers three output voltages, thus converting *shaft data* to *synchro data* suitable for transmission to a remote point.

a. Description. A synchro transmitter or synchro generator looks like a motor (fig. 76). The stator has three windings, and the rotor has

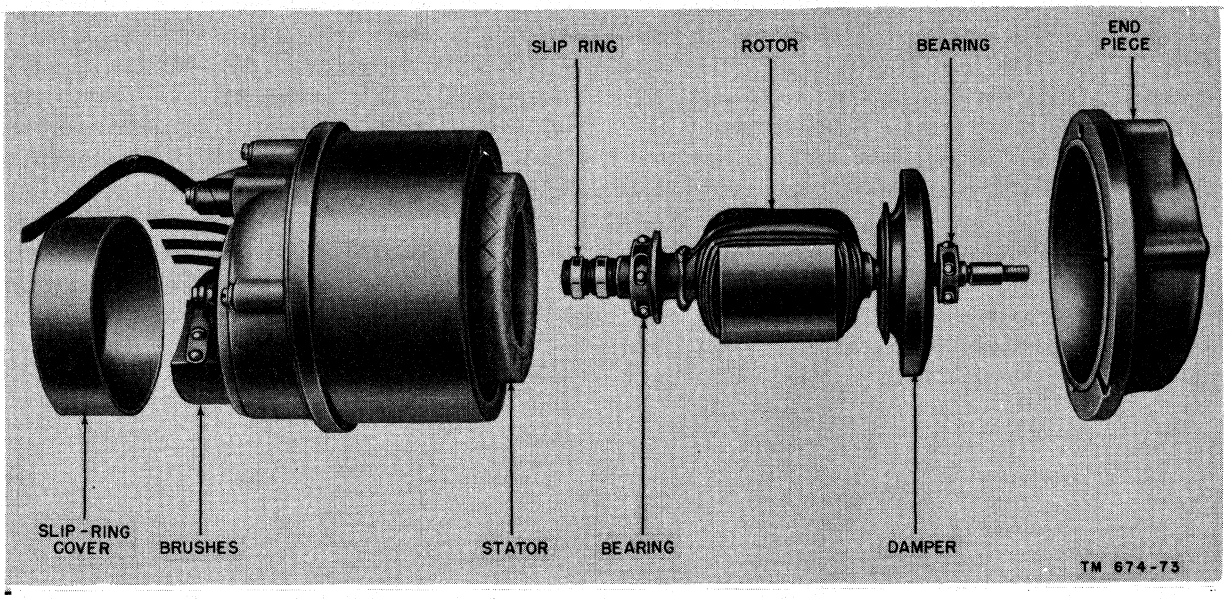


Figure 76. Synchro transmitter or synchro generator.

one. The complete synchro transmitter behaves like a variable transformer in which the rotor winding is the primary and the three stator windings are secondaries. The voltage induced in each of the three secondaries changes as the position of the rotor is altered. The rotor winding is connected, through brushes which ride on slip rings, to an a-c source which, on ships and in land installations, is usually 115 volts 60 cycles, and in aircraft is normally either 115 volts 400 cycles, or 24 volts 400 cycles.

b. Operation. A of figure 77 shows how a synchro transmitter operates as a variable transformer. There are two rotor positions for which the effective plane of the rotor winding is the same as that of stator winding 2. In either of these positions, all the magnetic field developed by the rotor current passes through the stator winding, and the voltage induced in the stator winding is greater for these positions of the rotor than for any others. In one of the two positions, the stator voltage will be in phase with the rotor-excitation voltage; in the other, the two voltages will have a phase difference of 180°. The position for which the voltages are in phase is called the zero or reference position of the rotor. As the rotor is turned from its zero position, less of the magnetic field passes through stator winding 2, and the level of the induced voltage falls off. The induced voltage for any position is proportional to the cosine of the angle through which the rotor has been turned. Therefore, the induced voltage falls to zero for a rotor angle of 90°, rises to its maximum level again at 180°, but, with a phase reversal since the cosine is negative, falls to zero at 270°, and rises again with its original phase as the rotor position approaches zero. This behavior may be represented by the projection of a vector on a line (B of fig. 77), where the length of the projected

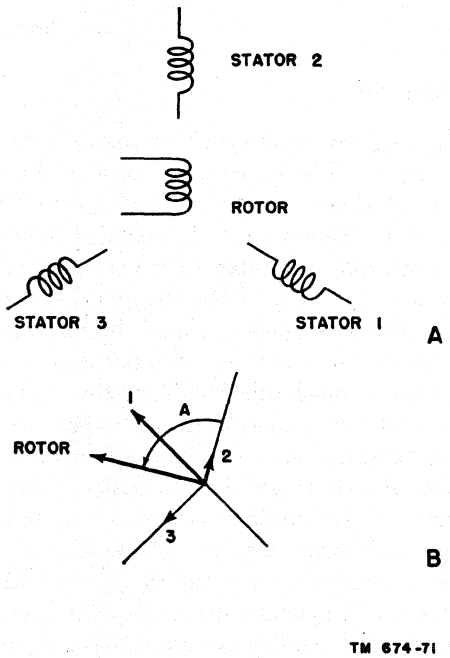


Figure 77. Induced stator voltages in synchro transmitter.

vector is equal to that of the original vector times the cosine of the angle between the positive direction of the line and the direction of the vector. The three stator windings are arranged symmetrically, having angles of 120° between them. The three voltages induced are then as shown in B, where A is the angle through which the rotor has been turned. In the zero position, the voltage induced in stator winding 2 is in phase with the rotor voltage and at its maximum level. The voltages induced in the other two stator windings are equal to each other and both are 180° out of phase with the rotor voltage. The positive direction of rotation is that for which the voltage in stator winding 1 is increased, and that in stator winding 3 falls toward zero. In most synchros, the shaft extends from the synchro body only at one end. When the synchro is viewed from this end, positive rotation is usually counterclockwise.

c. Output. The magnetic field of a synchro transmitter rotor always can be considered as the sum of two fields (A of fig. 78), one in the direction of the rotor field when the rotor is in zero position, the other perpendicular to that direction. The first field induces some voltage in stator winding 2, shown in B, and voltages half as great and 180° different in phase (since the cosine of 120° is minus ½) in stator windings 1 and 3. The sum of these three voltages is zero. The second field induces no voltage in stator winding 2, and induces equal voltages having opposite phases in stator windings 1 and 3. The sum of these voltages also vanishes. It follows, therefore, that the sum of the three stator voltages is always zero for any rotor position (if phase is taken into account). If the three stators are connected in a wye, as in C, and then connected to equal loads, the sum of the load currents will be zero, and no conductor will be required to carry the return current of the wye. The synchro thus requires two input leads to the rotor and only three output leads from the stators.

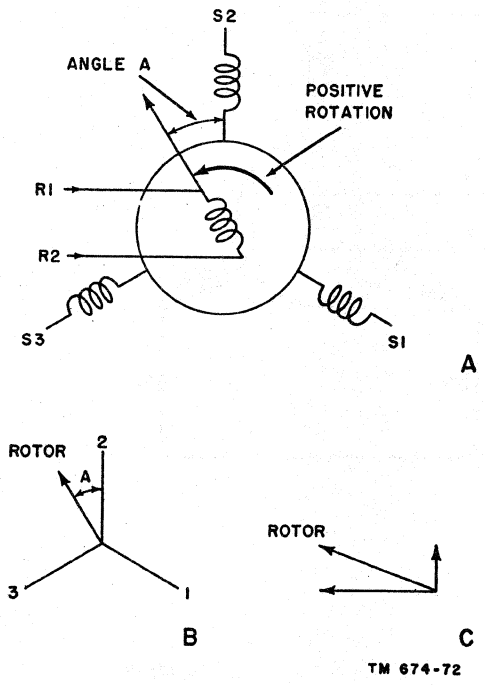


Figure 78. Synchro transmitter stator connections.

71. Synchro Receiver

A synchro receiver takes in synchro data and sets its own shaft to agree with the shaft position of the synchro transmitter to which it is connected. It develops but little torque and normally is used only to set dials or pointers, serving as a simple remote indicator.

a. Description. A synchro receiver or synchro motor (fig. 79) is electrically similar to the synchro transmitter. Physically it differs by having a mechanical damper on its shaft and by having bearings with very low friction. These are lubricated with light oil, whereas the bearings of a synchro transmitter normally are filled with grease. The damper is free to rotate on the synchro shaft but is partially restrained by friction disks which are rigidly connected to the shaft, thus preventing the synchro receiver from spinning as a synchronous motor. The damper accomplishes this because it has a high moment of inertia and, consequently, requires a high torque for acceleration. If the incoming synchro data direct the synchro receiver to change its position suddenly, the damper will not follow the synchro shaft but will, instead, exert a braking, or damping, torque through the friction disk, thus preventing overshoot. For synchro data directing a slow position change, however, the damper moves with the shaft.

b. Operation.

(1) A synchro receiver is connected to a synchro transmitter, as shown in figure 80. Its operation can be understood by noting that the current through each receiver stator winding is proportional to the voltage induced in the corresponding transmitter stator winding. The three

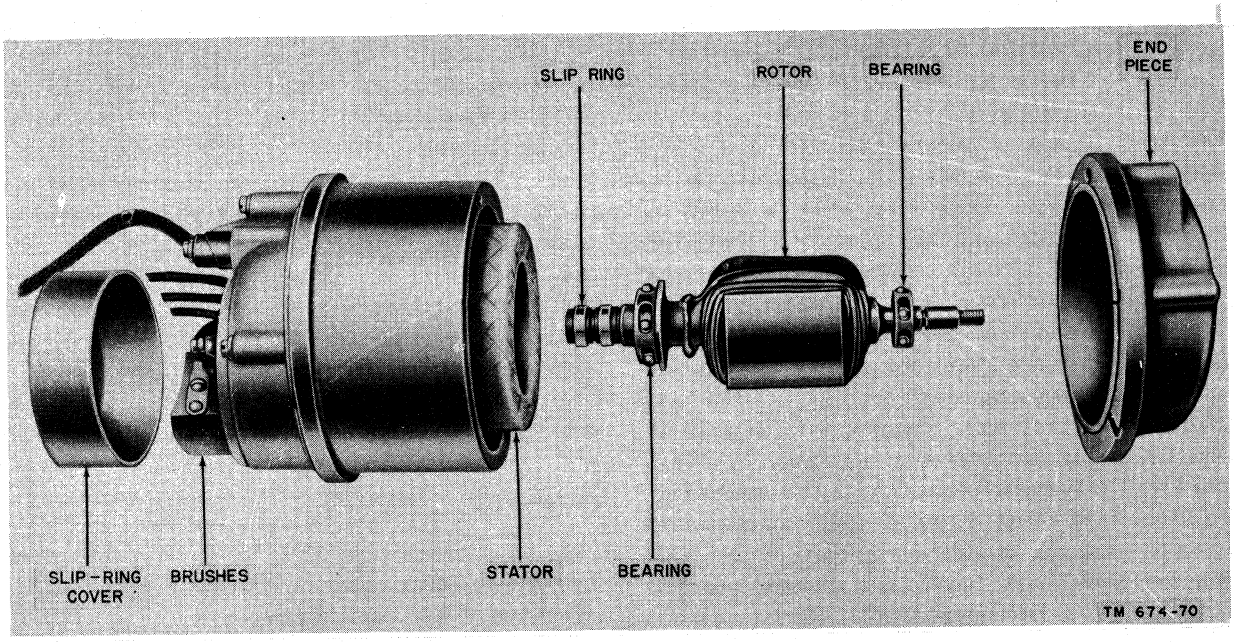


Figure 79. Synchro receiver or synchro motor.

stator windings, therefore, produce magnetic fields which, when added, result in a combined field whose orientation is the same as that of the rotor field in the transmitter. That is, the direction of the combined fields, relative to the synchro receiver stator structure, is the same as that of the transmitter rotor field relative to the transmitter stator structure. Operation may be considered as interaction between the receiver rotor and a magnetic field equivalent to that of the transmitter rotor. Since the receiver rotor acts like a magnet whose

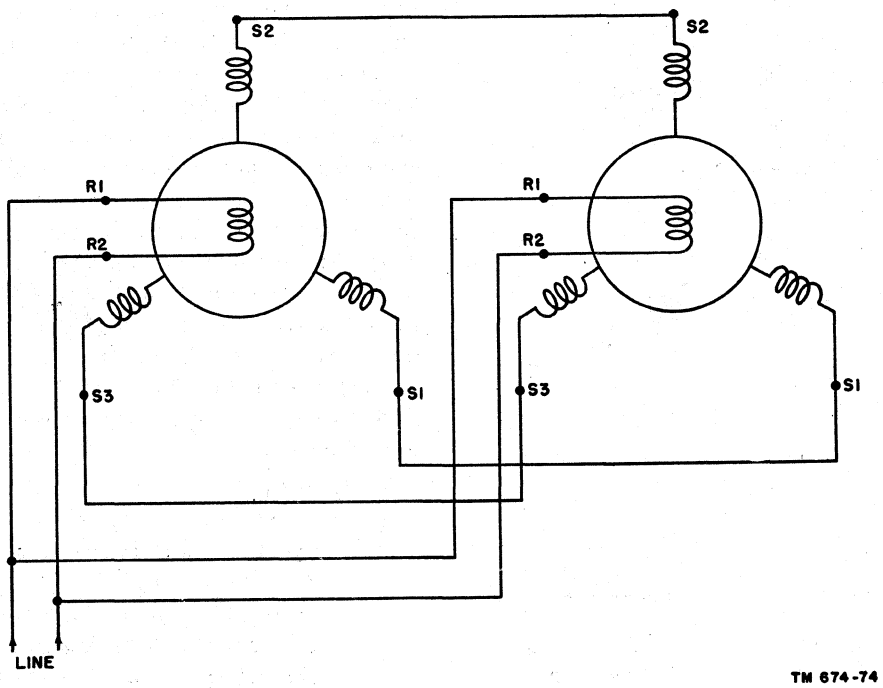


Figure 80. Synchro receiver connected to synchro transmitter.

poles are reversed with each reversal of the a-c excitation, it lines up with the equivalent rotor field, which also reverses with each reversal of the a-c excitation.

(2) This brings the synchro receiver rotor to a position relative to its stator that is the same as that of the transmitter rotor relative to the transmitter stator. A possibility of spinning arises because the positioning torque pulsates at twice the a-c frequency, reaching a maximum each time the two rotor currents reach a peak in either direction. If the rotor spins at synchronous speed, 1 revolution per cycle, the torque will have some value when the current reaches a peak in one direction, and exactly the opposite value when the current reaches a peak in the opposite direction, because the rotor has turned 180°. The average value of the positioning torque then is zero. Because of its shape, however, the rotor will tend to line up with the stator field at each current peak. Since this effect is caused by the magnetism induced by the stator field, the rotor can line up equally well in either of two positions which are 180° apart. If the rotor turns 180° each half-cycle, it will be alined with the stator field at each torque pulse and will continue to spin. The damper does not stop spinning, but does prevent the synchro receiver rotor from reaching synchronous speed, so that it cannot start spinning.

72. Synchro Control Transformer

A synchro control transformer receives electrical synchro data and also has its shaft set mechanically. It develops an output voltage that is determined by the difference between the actual shaft position and the position called for by the synchro data. It thus combines the functions of data receiver, follow-up, and sensing element. It normally controls a positioning servo which sets the control transformer shaft (as a follow-up shaft) at the same time that it positions a load in accordance with the synchro data.

a. Description. A synchro control transformer is similar electrically to a synchro transmitter,

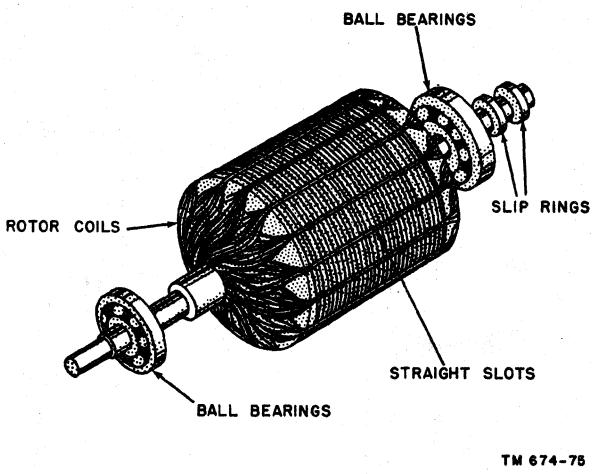


Figure 81. Synchro control transformer rotor.

but the iron core of its rotor is shaped differently to avoid distortion of the stator field when the rotor is not in a position equivalent to that of the transmitter rotor (fig. 81).

b. Operation. The synchro control transformer is connected to the synchro transmitter in the same way as a synchro receiver, except that the rotor of the control transformer is not connected to the line (fig. 82). Instead, the control transformer rotor delivers an error signal that usually is passed (directly or through various damping and transfer networks) to a controller. As before, the three stator windings of the control transformer reproduce the field of the transmitter rotor. The output voltage induced in the control transformer rotor is then proportional to the cosine of the angle between the control transformer rotor position relative to its stator structure and the position of the transmitter rotor relative to the transmitter stator structure. For any position of the transmitter rotor, there are two positions of the control transformer rotor for which no voltage is induced. The servo, however, will drive toward one position and away from the other. The zero position of the control transformer rotor is one for which there is no induced voltage when the control transformer is connected to a transmitter whose rotor is at zero position. There are two positions for which this is true. The zero position is the one for which a slight positive (counterclockwise) rotation of the control transformer results in an output having the same phase as the excitation of the transmitter rotor.

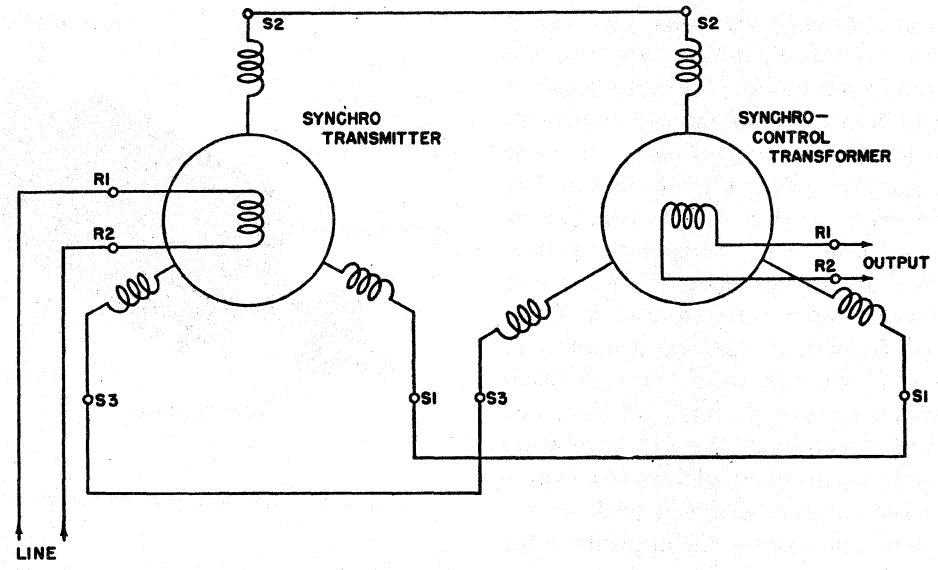


Figure 82. Synchro control transformer connected to synchro transmitter.

73. Synchro Differential Transmitter

A synchro differential transmitter receives both electrical and mechanical inputs. Instead of developing an error voltage, however, its output is synchro data. If the incoming synchro data are equivalent to shaft angle A of figure 83, and the mechanical shaft setting of the synchro differential transmitter is shaft angle B, the electrical output is synchro data equivalent to shaft angle (A−B) or, by a change in connections discussed in paragraphs 76 and 77, equivalent to shaft angle (A+B).

a. Description. The stator of a synchro differential transmitter is the same as the stators of the other synchros already discussed. The rotor, however, has three windings. These are connected in a wye like the stator windings, as indicated in figure 83.

b. Operation. The stator of a synchro differential transmitter is connected in the usual way to the stator output of a synchro transmitter, and the stator windings of the differential reproduce the rotor field of the synchro transmitter (fig. 83). This induces voltages in the three windings of the differential rotor, exactly as the field of the transmitter rotor induces voltages in the windings of

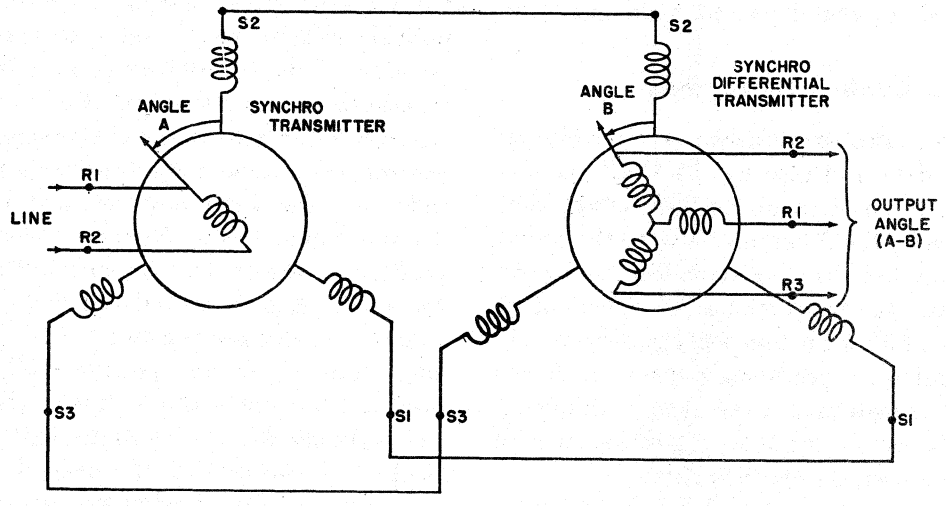


Figure 83. Synchro transmitter connected to synchro differential transmitter.

the transmitter stator. The resulting output voltages are treated in exactly the same way as those of an ordinary synchro transmitter. Thus, if the synchro differential is set at zero, its output will be the same as that of the synchro transmitter which feeds it. If, however, the differential rotor is turned, the effect on the output will be the same as that of turning the transmitter rotor in the opposite direction. This is because the differential stator reproduces the field of the transmitter rotor, and the differential rotor takes the place of a transmitter stator. Positive rotation of the differential rotor is thus equivalent to positive rotation of the transmitter stator, or negative rotation of the transmitter rotor.

74. Synchro Differential Receiver

A synchro differential receiver is connected to two synchro transmitters, either directly or through differential transmitters, and sets its shaft to the difference between the transmitted shaft angles. It develops low torque and is used as a remote indicator in the same way as the synchro receiver.

a. Description. A synchro differential receiver is electrically and physically similar to a synchro differential transmitter, with the exception that it has a mechanical damper like that of the synchro receiver.

b. Operation. A synchro differential receiver is connected as shown in figure 84. The stator windings reproduce the magnetic field of one transmitter rotor, and the rotor windings reproduce the field of the other. Since the motor has a field like a transmitter rotor, it acts like one (or like the rotor of the synchro receiver) and lines up with the field. As before, the damper is required to avoid spinning. If the input data to the stator are equivalent to shaft angle A, figure 84, and the input data to the rotor are equivalent to shaft angle B, the synchro differential receiver will set its own shaft to angle (A−B).

75. Zeroing Procedure

It is necessary for all of the elements of a synchro data-transmission system to be synchronized if it is to operate properly. That is, the synchro receivers must read correctly and the synchro-control transformers must cause their associated servos to position loads properly. It is possible to set all of the input shafts and then rotate the receivers and control transformers in their mountings until proper results are obtained. The various components usually are so far apart, however, that this is inconvenient. Instead, each component is adjusted individually so that it operates correctly at zero or reference position. For example, the device which sets a synchro transmitter is set at its reference position. The synchro transmitter then is loosened in its mounting and its stator is rotated until its output corresponds to a zero shaft position. If this is done for all of the synchros in the system, the system will operate properly. The only equipment required for zeroing is a voltmeter. This should have a high range with an input of one and three-quarters or two times the synchro excitation voltage for

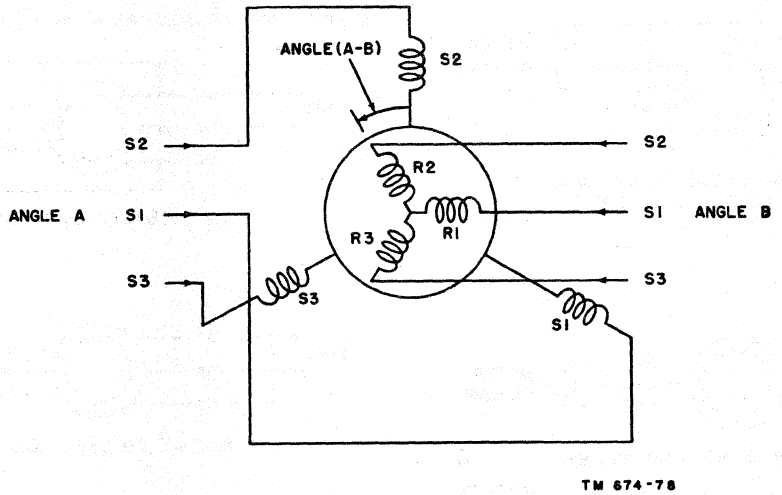


Figure 84. Synchro differential receiver connections.

full-scale deflection, and a low range with an input of about 1/20 of the excitation voltage for full-scale deflection. If no meter is available, a lamp, or two lamps in series, may be used when the high range is called for, and a pair of headphones for the low range. Dim lamps or low output from the headphones are the equivalent of a low meter reading. For zeroing 115-volt synchros, two 115-volt lamps, in series, must be used, since a single lamp will burn out if connected to a high-voltage source.

a. Zeroing a Synchro Transmitter. To zero a synchro transmitter, remove the stator leads and set the equipment to which the synchro is connected exactly on zero, loosen the clamps that hold the synchro housing in its mount, and follow the steps shown in A of figure 85. If there is no voltage between S1 and S3, the voltages induced in the stator windings to which these are connected must be equal. The synchro is therefore either at zero or at 180°. The ambiguity is resolved by connecting S3 to one side of the line, R2, and reading the voltage between S2 and the other side of the line, R1 (B of fig. 85). Since the voltage between S2 and S3 is in phase with the line voltage at zero, and 180° out of phase with it at 180°, the meter will read lower at zero than at 180°. When the synchro is definitely near zero, a precise adjustment may be made using the low range of the voltmeter (C of fig. 85). Following this, the housing is clamped tight in the mounting and the stator leads are reconnected.

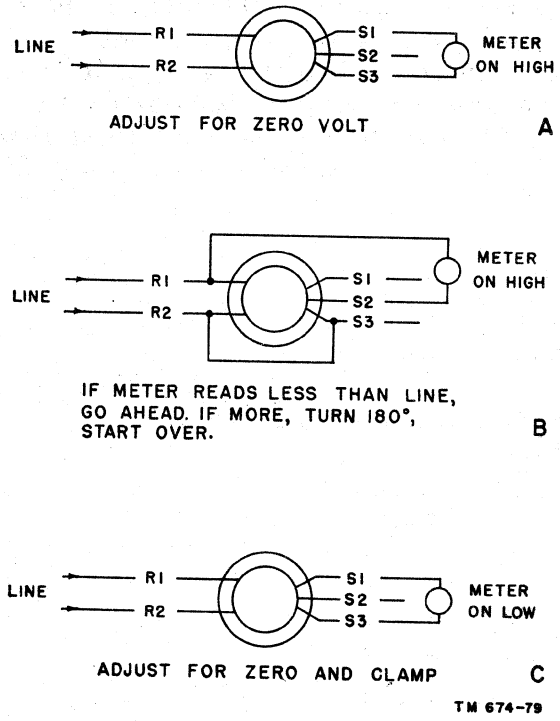


Figure 85. Zeroing a synchro transmitter.

b. Zeroing a Synchro Differential Transmitter. Remove all leads from the synchro, set the equipment on zero, and loosen the clamps. Zero is determined approximately by connecting S1 and S2 to the line (A of fig. 86), and turning the stator in its mount until the voltage between R1 and R2 is at a maximum in phase with the line. This will give a minimum meter reading. One side of the line then is connected to S2 (B of fig. 86), the other to S1 and S3, in order to simulate a zero electrical input. Precise adjustment is obtained on a low meter scale by reading the voltage between R1 and R3. During this procedure, the synchro differential generator is excited at a higher level than normal. Therefore it should not remain connected to the line longer than is necessary for the adjustment. When adjustment has been completed, tighten the mounting clamp and reconnect the leads.

c. Zeroing a Synchro Control Transformer. Remove all leads from the synchro, set the equipment on zero, and loosen the mounting clamps. Determine approximate zero as that position in which the rotor voltage is a maximum in phase with the S3, S1 voltage (A of fig. 87). Next, simulate an input of electrical zero shown in B of figure 87, and make a fine adjustment with the meter on low scale. Tighten the clamps and reconnect the leads. As before, the synchro control transformer is excited at a higher level than normal, and should not remain connected to the line longer than necessary. When no bias is used, the synchro is set

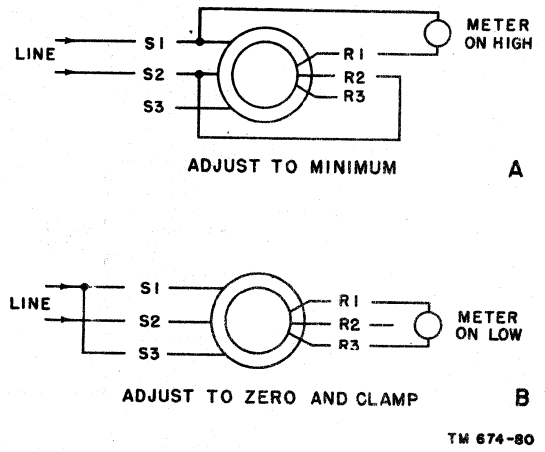


Figure 86. Zeroing a synchro differential transmitter.

so that its output is zero for an input of electrical zero. In many cases, particularly with coarse synchros, bias is added to the synchro output. The combined signal—synchro output plus bias—must then be zero for an input of electrical zero and the meter must be connected as shown in B, so that it reads the sum of the two voltages. This may be omitted in the preliminary adjustment shown in A (although this step may also be made with the bias circuit connected), but the final adjustment always must be made on the basis of combined synchro output and bias.

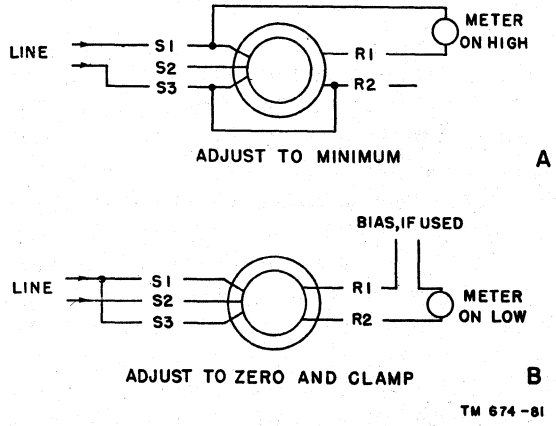


Figure 87. Zeroing a synchro control transformer.

d. Zeroing a Synchro Receiver. To zero a synchro transformer, remove the stator leads, loosen the clamps, and connect as shown in figure 88 to simulate a zero-position input. The synchro receiver will set itself to electrical zero, and it may be rotated in its mount until a dial or pointer reading of zero is obtained. Tighten the clamps and reconnect the leads. Do not leave the synchro connected to the line longer than necessary.

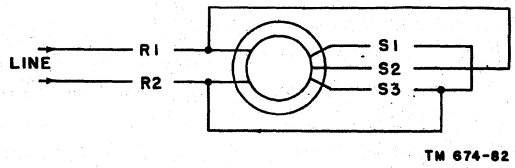


Figure 88. Zeroing a synchro receiver.

e. Zeroing a Synchro Differential Receiver. Remove all leads from the synchro, loosen the clamps, and connect as shown in figure 89 to simulate zero electrical input to both rotor and stator. Rotate the synchro in its mount until zero dial or pointer reading is obtained, clamp, and reconnect the leads. Do not leave the synchro connected to the line longer than necessary.

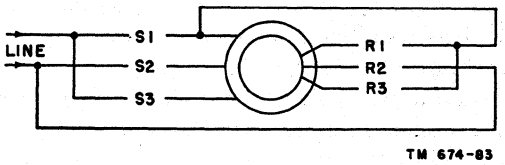


Figure 89. Zeroing a synchro differential receiver.

76. Reversing Synchro Rotation

When a synchro transmitter is at its reference position, there is no voltage between S1 and S3. As it turns off zero in one direction, the voltage induced in one of these coils is increased and that induced in the other is decreased. Reversing the rotation will reverse the voltage changes. It is possible, therefore, to reverse the leads from S1 and S3 so that the synchro may be turned clockwise, although the output voltages on the three leads act as if it were being turned counterclockwise. That is, the synchro data indicate a positive rotation when the synchro has been rotated in the negative direction. This is the only permissible change in the connections. Any other change will shift the position of electrical zero (the synchro data will not be equivalent to zero when the synchro shaft is at zero position) and will cancel all the advantages gained by the possibility of zeroing each component separately. With synchro receivers and control transformers, it also is permissible to interchange the leads from S1 and S3, and with differential transmitters and receivers R1 and R3 may be interchanged as well. No other changes can be made.

77. Standard Connections

To avoid detailed examination of a system to insure that connections are correct for the direction of rotation at each synchro, it is usual to make all connections so that the synchro data behave as if positive rotation is associated with increasing values of the quantity being transmitted. For this reason, standard designations are desirable for the synchro busses that carry the data. The following designations and connections are standard with the Navy and normally are followed by the other services.

a. Bus Designations. Bus designations are as shown in figure 90. The lines which carry the synchro data for a single quantity are designated by letter and number; here the letter is B. The excitation lines are B and BB; the lines for coarse data are B1, B2, and B3; and the lines for fine

data are B4, B5, and B6. In the event coarse, intermediate, and fine synchros are used, B4, B5, and B6 are connected to the intermediate synchro and B7, B8, and B9 to the fine synchro. The following discussion assumes only fine and coarse synchros. The letter B may be replaced by any other letter and number combination, as long as the combination ends in a letter. For example, the third set of synchro data to equipment G might be carried on busses designated 3G, 3G–G, 3G–1, 3G–2, 3G–3, 3G–4, 3G–5, and 3G–6, the combination being 3G. If only single-speed data are carried, busses –4, –5, and –6 are omitted.

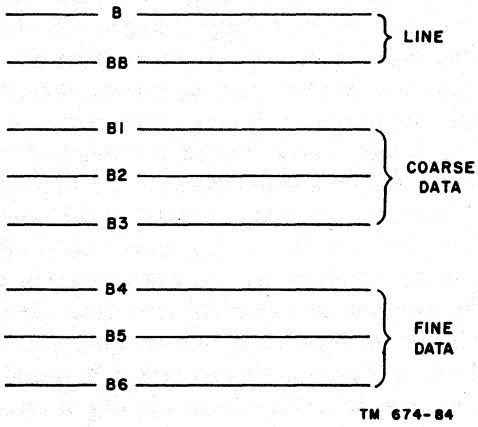


Figure 90. Standard bus designations.

b. Synchro Transmitter Connections. If the synchros turn counterclockwise, as viewed from the shaft and, when the quantity transmitted is increasing (fig. 91), the coarse synchro is connected R1 to B, R2 to BB, S1 to B1, S2 to B2, S3 to B3, and the fine synchro is connected R1 to B, R2 to BB, S1 to B4, S2 to B5, S3 to B6. If either synchro turns clockwise (fig. 91), for an increase in the transmitted quantity, the connections to S1 and S3 are interchanged.

c. Synchro Receiver Connections. These are the same as the connections described in *b* above for synchro transmitters.

d. Synchro Control Transformer Connections. These are the same as those described above for synchro transmitters, except that R1 and R2 are connected to the controller (directly or through various networks instead of to the B and BB line).

e. Synchro Differential Transmitter Connections. Normal connections for the coarse differential are B1 to S1, B2 to S2, B3 to S3 of the incoming bus group, and R1 to B1, R2 to B2, R3

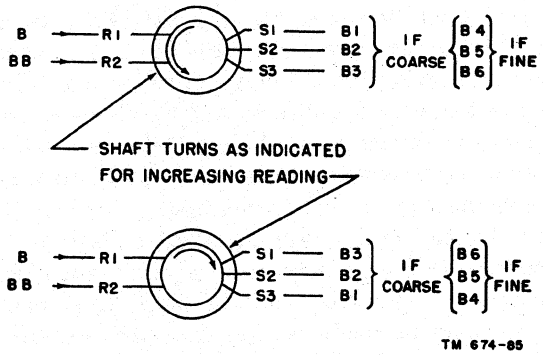


Figure 91. Standard connections for synchro transmitter.

to B3 of the outgoing bus group, as shown in figure 92. Normal connections for a fine differential are S1 to B4, S2 to B5, S3 to B6 of the incoming bus group and R1 to B4, R2 to B5, R3 to B6 of the outgoing bus group. With these connections, the synchro differential subtracts its own shaft angle from that of the synchro transmitter that feeds it. To make the differential add instead of subtract, interchange the leads to S1 and S3 and interchange the leads to R1 and R3. This assumes that the differential turns counterclockwise with an increase in the quantity it transmits. If it turns clockwise with an increase, it will add with normal connections and subtract with reversed connections.

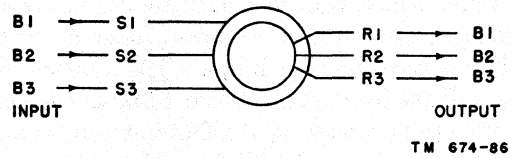


Figure 92. Standard connections for synchro differential.

f. Synchro Differential Receiver Connections. With the connections as shown in figure 93, an increasing quantity sent to the stator will cause the differential receiver to rotate counterclockwise as viewed from the shaft end, and an increasing quantity sent to the rotor will cause it to rotate clockwise. Either or both of these directions may be reversed by interchanging the S1, R1 and S3, R3 leads.

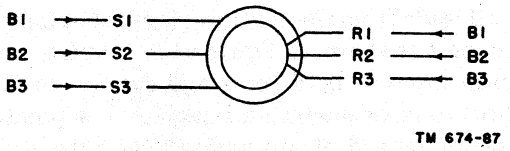


Figure 93. Standard connections for synchro differential receiver.

78. General

A resolver, like a synchro, has rotor and stator windings and behaves like a variable transformer. Two stator windings act as primaries, and two rotor windings act as secondaries. Unfortunately, there is no standard system of designating the various leads. Some resolvers have separate connections to each winding, and others use one common lead for the primaries and another for the secondaries. Some models have extra windings for feedback, and others omit either one primary or one secondary. In some cases, primary windings are carried on the rotor and secondaries are wound on the stator. Figure 94 shows a set of resolver windings with the rotor in its zero position. The designations P and S refer to *primary* and *secondary*. The magnetic coupling in the zero position is such that excitation of P1–P3 induces maximum voltage, of the same phase, in the S1–S3 secondary and no voltage in the S2–S4 secondary. Excitation of P2–P4 induces maximum voltage of the same phase in the S2–S4 secondary and no voltage in the S1–S3 secondary. With slight positive rotation, the voltage induced in S1–S3 is in phase with the P2–P4 excitation, and the voltage induced in S2–S4 is 180° out of phase with the P1–P3 excitation. This arrangement is representative of usual resolver practice.

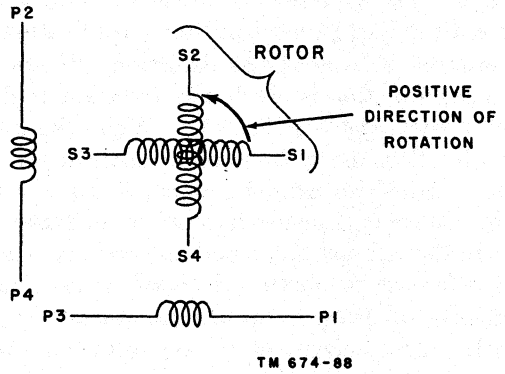


Figure 94. Schematic representation of resolver.

79. Magnetic Field of Primaries

The output of each resolver secondary depends on both primary voltages, and also on the rotor position. In practice, however, the resolver generally is used in a computing system where voltages serve to represent positive and negative quantities. *Positive* voltages are then in phase with some convenient reference voltage, and *negative* voltages are in antiphase (180° out of phase) with the reference. The total magnetic field is that produced by the combined primary currents, and this is the sum of the two separate fields which are added by vector addition (fig. 95). The method of combining the fields is identical with the one used in paragraph 48. In the case of the resolver, the combined field does not rotate in space because the two component fields are in phase with each other.

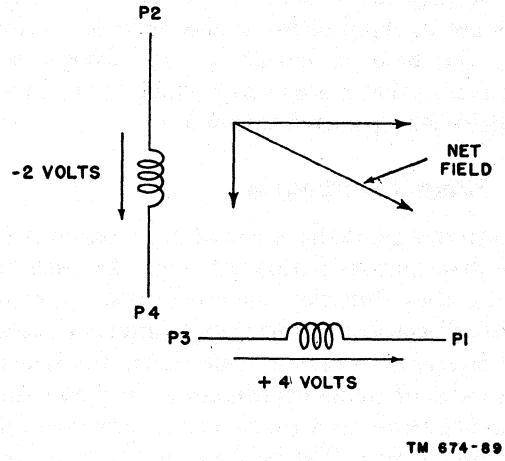


Figure 95. Field produced by resolver primary windings.

80. Voltages Induced in Secondaries

The behavior of each resolver secondary is like that of a synchro control transformer rotor winding. The two primaries establish a magnetic field having a certain strength and direction. The voltage induced in each secondary is proportional to the component of the combined field that lies in a direction perpendicular to the plane of the secondary winding. If the rotor is turned so that no voltage is induced in one secondary, the output of the other secondary will be at a maximum, and will be proportional to the strength of the combined primary field. It is customary to adjust the ratio of primary and secondary turns so that the output is equal to the input when the rotor is turned to maximize the coupling. In the zero rotor position the output at S1–S3 is equal to the input at P1–P3. Similarly, the output at S2–S4 is equal to the input at P2–P4. B of figure 96 shows a positive voltage induced in S1–S3; a nega-

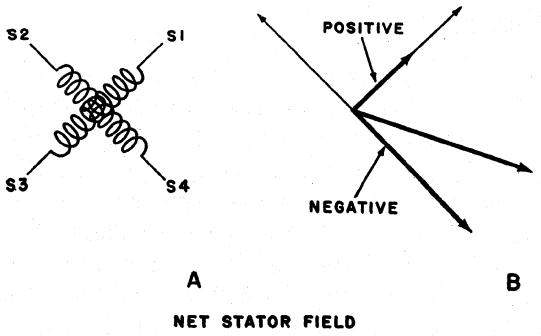


Figure 96. Voltages induced in resolver secondaries.

tive voltage induced in S2–S4 when the secondaries are in the position is shown in A. (Normally, the field is considered as always being positive, so that a secondary which is alined with the field has a positive output.)

81. Plane Coordinates

Resolvers generally are used in computers of the type described in paragraph 114. In such computers, they function as coordinate converters. Before discussing resolver applications, therefore, it is desirable to review some of the fundamental properties of plane coordinates. Suppose that a reference point in a plane and a reference direction are chosen. The position of any other point in the plane then can be described by two numbers called coordinates. In the case of Cartesian coordinates, or x–y coordinates, both of the numbers correspond to distances. In the case of polar coordinates, one corresponds to a distance and the other corresponds to a direction.

a. Plane Cartesian or X–Y Coordinates. In plane Cartesian or x–y coordinates, the position of a point is given in terms of two distances. The coordinate system consists of two axes that are perpendicular to each other. The point of intersection of the axes is called the origin, and the coordinate system is fixed in the plane so that the origin lies at the reference point. The positive direction along one of the axes lies in the reference direction, and the positive direction of the other is perpendicular to the reference direction. The two coordinate distances are then the vector components, parallel to the axes, of the distance between the origin and the point in question. A, figure 97, shows a point with coordinates 2 and 3, and B shows a point with coordinates −1 and +2.5. The directions of the positive axes may be called north and east, in which case the second point lies one unit south of the origin, or forward and to the right, or any other pair of perpendicular directions.

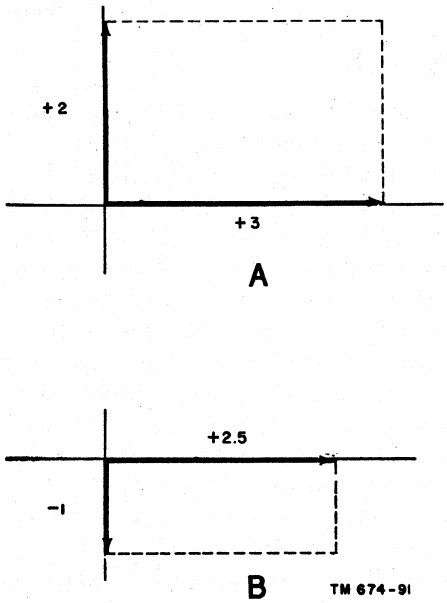


Figure 97. Plane Cartesian coordinates.

b. Polar Coordinates. The coordinates of a point in a polar coordinate system are the distance and direction of the point from the origin. The distance customarily is called range and is always positive. The direction is measured from a reference direction; in most military applications it is measured in a clockwise direction. When the reference direction is north, the direction angle is called a bearing (B of fig. 98). When the reference direction, as in A, is other than north, the angle is called an azimuth angle, or simply azimuth. *Bearing* is primarily used in the Navy and the Air Force, since ships and aircraft are steered with reference to north. *Azimuth* is used more commonly in Army installations, since it is frequently more convenient to use reference directions other than north—as, for instance, a line between an emplacement and a distant, clearly visible landmark.

c. Coordinate Conversion. The method of converting from one coordinate system to the other is shown in figure 99. Plane Cartesian coordinates may be added, by vector addition, to find polar coordinates. Conversely, the plane Cartesian coordinates are the components, parallel to

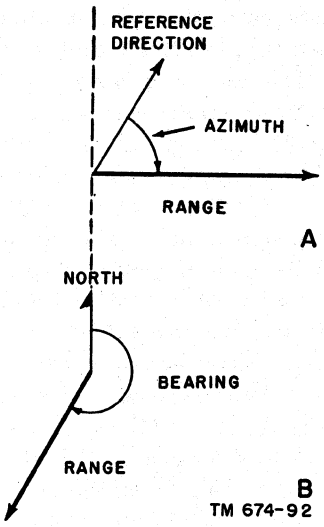


Figure 98. Polar coordinates.

the coordinate axes, of the polar coordinate vector. In a resolver, the primary voltages may be thought of as plane Cartesian coordinates. The primary windings then produce magnetic fields which are the Cartesian vector components of a combined field that can be expressed in polar form (field strength and direction). The voltages induced in the secondaries are the Cartesian vector components of the combined field for a different set of Cartesian axes.

d. Rotation of Axes. The problem of rotating a set of plane Cartesian coordinate axes is shown in figure 100. Consider the operation as taking place in three steps. Convert the plane Cartesian coordinates of any point to polar coordinates. The reference direction of the polar coordinate system then is rotated through any desired angle. (Positive rotation of the reference direction simply reduces the angular coordinate, bearing

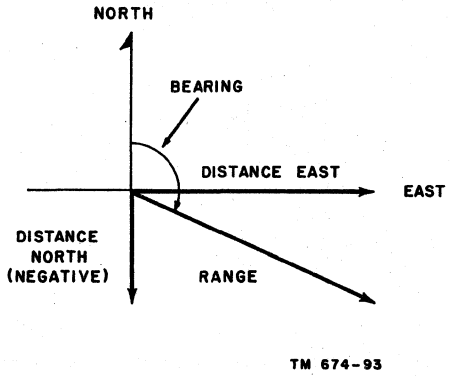


Figure 99. Conversion of coordinates.

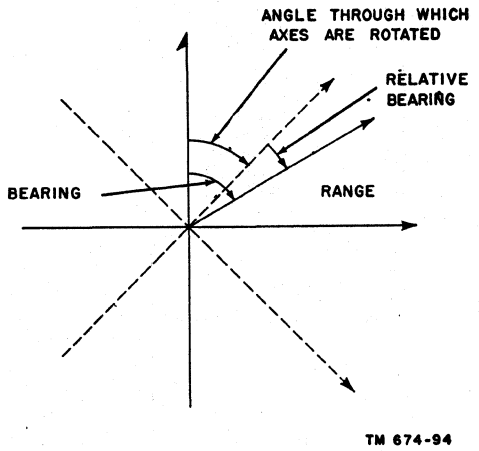


Figure 100. Rotation of Cartesian axes.

or azimuth, by the amount of rotation.) The new polar coordinates then are converted to plane Cartesian coordinates.

82. Resolver as Computing Element

In these examples, the resolver is used to carry out the three transformations discussed in paragraph 81*d*; conversion from polar to plane Cartesian coordinates, rotation of Cartesian coordinate axes, and conversion from plane Cartesian to polar coordinates.

a. Conversion From Polar to Plane Cartesian Coordinates. This problem frequently arises when the range and bearing of a target are known and the distances north and east are required. As shown in A of figure 101, a voltage proportional to the range is applied to P2–P4, and the rotor is turned from the zero position in the positive shaft direction (counterclockwise) through an angle equal to the bearing. The vector diagrams in B and C show immediately that the distance north appears as a voltage at S2–S4, and the distance east appears at S1–S3. In vector diagram B, the vectors are alined with the axes of the resolver coils in the schematic, but in C, the vectors are tipped so that north is vertical, as is customary. A similar problem, which is handled in the same way, is the determination of the horizontal range and height of an airborne target when the slant range and elevation angle are known. This is discussed in paragraph 118.

b. Rotation of Cartesian Coordinate Axes. This problem does not arise in practice as frequently as the one discussed above, but is a good example of resolver operation. On a ship, bearing angles

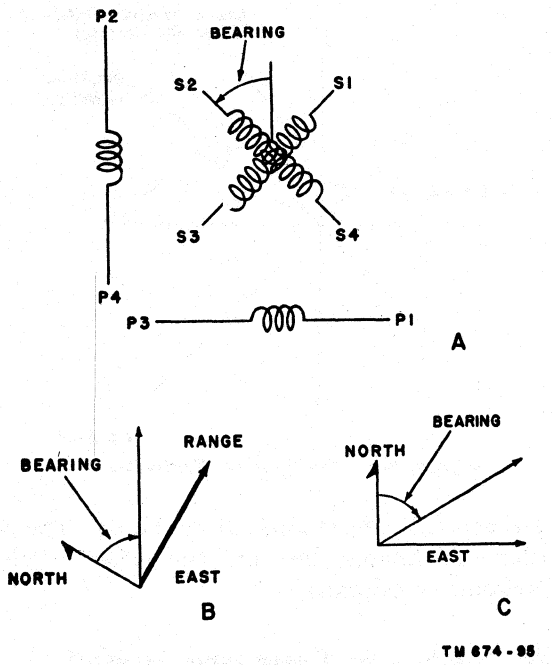


Figure 101. Conversion from polar to plane Cartesian coordinates in resolver.

customarily are measured either from north or from the forward direction. Angles measured from north are called *bearings;* those measured from the forward direction are called *relative bearings.* Examination of A of figure 102, shows that the *bearing* of a target is the sum of the *relative bearing* and the course of the ship, since this course is the angle measured from north to the forward direction. Suppose, then, that the position of a target is given in plane Cartesian coordinates as distance forward and distance to the right, and that it is necessary to convert these to distance north and distance east. Voltages proportional to the forward distance and distance to the right are applied, respectively, to P2–P4, and to P1–P3 (B of fig. 102). The resulting magnetic field then has a strength proportional to the range, and a direction, relative to the stator, which is the same as the relative bearing. The rotor now may be turned counterclockwise, as in C, through angle Y, equal to the course angle, and the secondary voltages will be distance north at S2–S4, and distance east at S1–S3.

c. Conversion From Plane Cartesian to Polar Coordinates. This is another problem that arises frequently. Given the plane Cartesian coordinates of a target, distances north and east, find the polar coordinates, range and bearing. Voltages proportional to distance north and distance east are applied, respectively, to P2–P4, and to P1–P3 (A of fig. 103). The resulting magnetic field has a strength proportional to the range, and a direction the same as the bearing. If, therefore, the rotor is turned in the negative direction (clockwise) through angle X, equal to the bearing in B, a positive voltage proportional to the range will be induced in S2–S4, and no voltage induced in S1–S3. In practice, a servo is used to position the rotor, as in C, so that there is no output from S1–S3. There are two such positions, but the servo drives toward one and away from the other. The required bearing is then the negative of the rotor position angle, and the range appears as a voltage at S2–S4. The resolver, in this case, functions as a computing component and develops its own position order

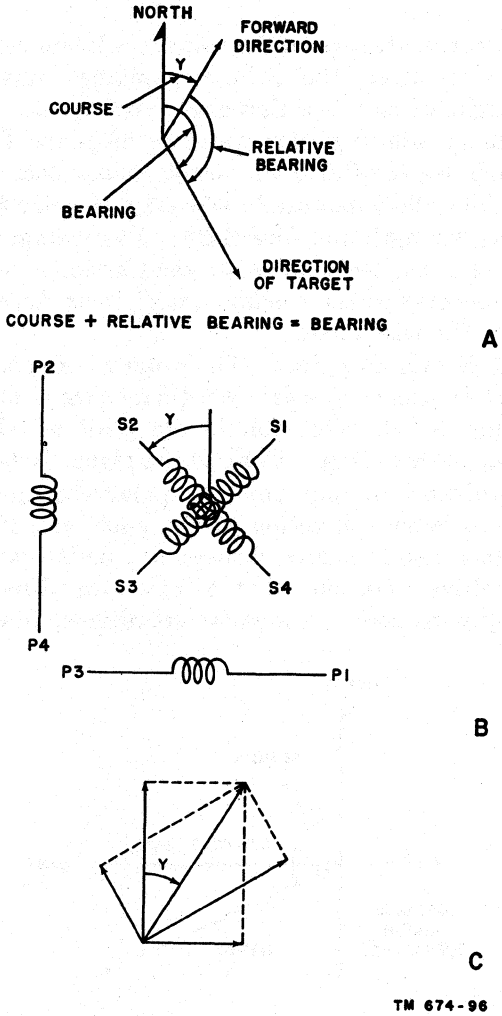


Figure 102. Rotation of plane Cartesian coordinate axes in resolver.

(in terms of the direction of the magnetic field) from the input voltages. It also serves as a follow-up and as a sensing element. The output from S1–S3 is proportional to the sine of the error angle and also proportional to the strength of the magnetic field. The servo thus becomes stiffer with increasing range; that is, when the range is increased, the stronger magnetic field develops a larger error voltage for a given angular error and the servo motor develops a greater torque. This makes it extemely difficult to damp such a servo, since it will be underdamped for long ranges and overdamped for short ranges. The problem is eliminated by using the variable-gain amplifier described in paragraph 62. The range voltage, from S2–S4, is used as a control voltage, and the error voltage, from S1–S3, is passed through the signal channel. With increasing range, the amplification is reduced so that the output of the variable-gain amplifier is substantially independent of range. The servo motor then develops a torque, for a given angular error, that is independent of range, and the servo can be damped easily.

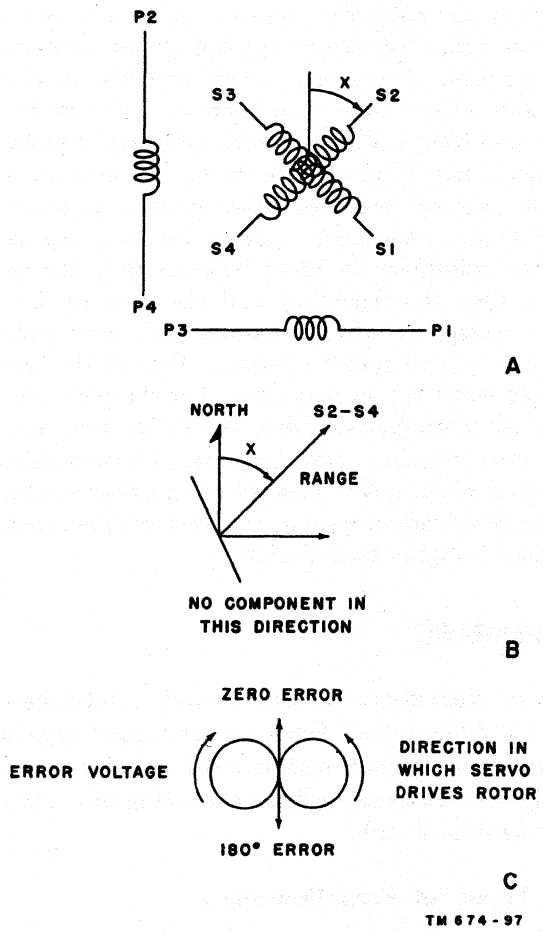


Figure 103. Conversion from plane Cartesian to polar coordinates in resolver.

83. Booster Amplifiers

Resolvers sometimes are excited through booster amplifiers. That is, the input voltage is fed to a booster amplifier which drives the resolver primary. Because it is not possible to use a coarse-fine system in resolver computing, as is done in data transmission with synchros, it is necessary to make every effort to minimize possible errors. The booster amplifier eliminates two of the worse errors, those resulting from winding resistance and leakage reactance in the primary and secondary.

a. Theory. Resolvers frequently are cascaded in chains of three or four. One of the input signals to the final resolver may pass through all of the preceding resolvers, whereas the other may pass through only one. In order to preserve the proper phases and levels, it is imperative that there be no change in level except as called for by the rotor position. Both of these results can be achieved if, first, the proper magnetic field is produced by each primary and, second, if neither secondary draws more than a negligible amount of current. Both of these requirements can be met by using booster amplifiers between the cascaded resolvers. The output of a secondary is fed to a booster amplifier, which has a high input impedance and draws almost no current, and the output of the booster drives the following primary. In order that the proper field may be produced, an auxiliary winding in the stator structure measures the field produced by the main winding, the voltage induced in the auxiliary being a measure of the field strength. The voltage from the auxiliary winding then is fed back to the booster input in opposition to the external signal, which normally comes from the preceding resolver secondary. The actual input seen by the first amplifier stage is then the difference between the external input and the follow-up input—a voltage which is proportional to the error in the strength of the field. The booster then acts like a servo and delivers the current required to produce the proper field. Two separate boosters are associated with each resolver, one to drive each primary. There are two auxiliary windings in the stator, one associated with each primary winding and its driving booster.

b. Application. In some cases, all computing voltages may originate at the two secondaries of a resolver having an input on only one primary. In figure 104, however, the booster driving that primary may be omitted, since any phase shift and change in level will be the same at both secondaries. In almost all other cases, a booster is used with each resolver primary that is excited.

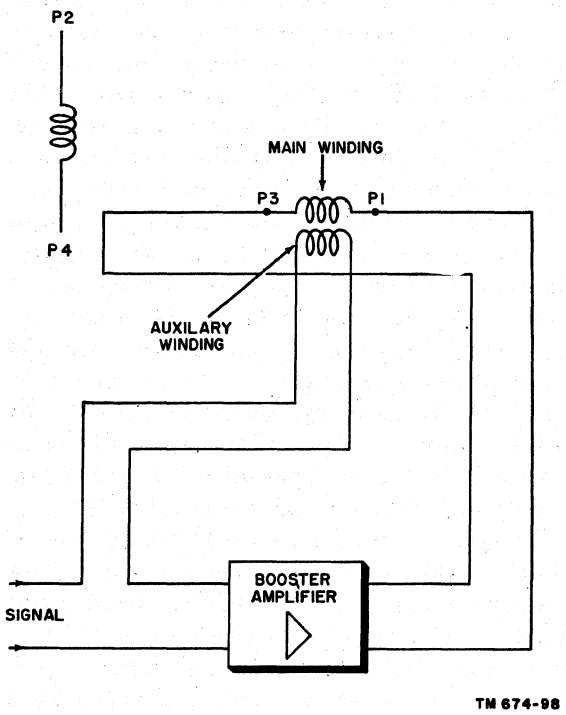


Figure 104. Connections to booster amplifier.

84. Resolver for Data Transmission

Resolvers normally are not used for data transmission. It is possible, however, to excite one primary of a resolver, use the two outputs to excite the primaries of a second resolver, and then drive the shaft of the second with a servo so that it repeats the shaft angle of the first. In terms of the transformations described above, the first resolver is given a fixed range (constant primary excitation on one winding, no excitation on the other) and any desired bearing (as a shaft angle). The outputs are the corresponding plane Cartesian coordinates. These may be fed to a second resolver for conversion back to polar form. The range output of the second resolver may be disregarded, and the negative of the shaft angle will be the bearing, which is the shaft angle of the first. By appropriate reversal of the connections to one secondary, the second shaft can be made to repeat the position of the first directly. Nevertheless, synchros are preferred for a number of reasons. The normal coarse-fine synchro system used in most applications is more accurate than a single pair of resolvers, for instance, and although a coarse-fine resolver system is even more accurate than the coarse-fine synchro system, the precision of the data rarely justifies its use. In addition, a coarse-intermediate-fine synchro system of comparable or greater accuracy requires no boosters. Where space is at a premium, a single pair of resolvers offers greater accuracy than a pair of synchros. These, however, require booster amplifiers (without boosters they are no better than the synchros) and also require four leads instead of three (besides the extra pair carrying the reference signal). Two of the secondary leads can be commoned, but the errors introduced lower the precision, and the resolver system still requires two boosters. Occasionally, however, where space does not permit the use of a coarse-fine synchro system, resolvers with boosters are used for data transmission.

Section VII. POTENTIOMETERS

85. Potentiometers Generally

A potentiometer is a tapped resistor, in which the position of the tap can be altered by some sort of mechanical control. The standard high-resistance potentiometer used in communications circuits uses a resistance element consisting of a thin film of carbon deposited on some insulating material. However, this is not practical for servo use because the resistance of such a carbon film changes with wear, and with variation in temperature and humidity. Since a more rugged type is required, the potentiometers used in servos generally use resistance elements consisting of a number of turns of wire.

86. Types of Potentiometers

a. Most potentiometers used in servos are essentially similar, consisting of wire resistors and

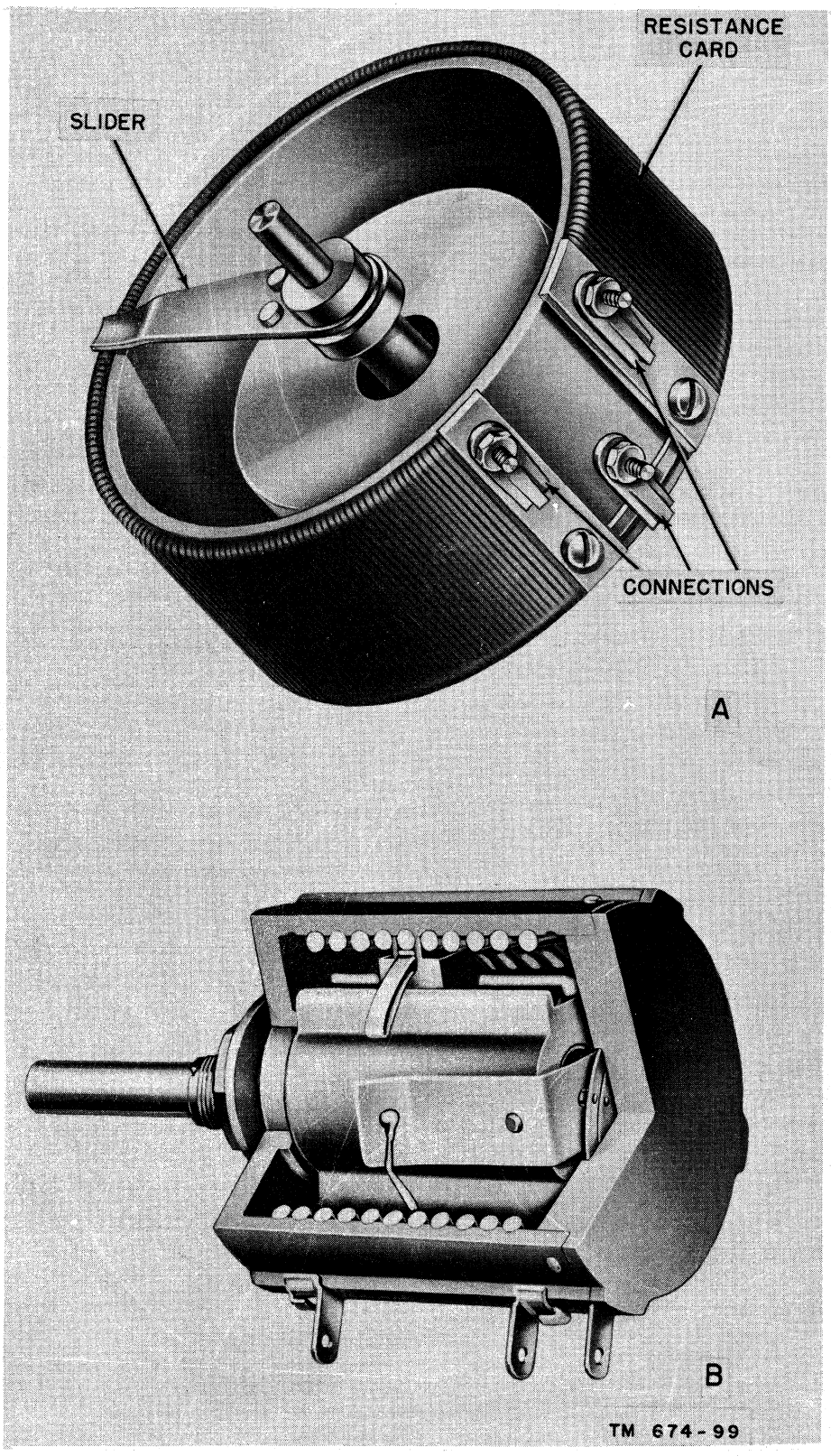


Figure 105. Linear potentiometers.

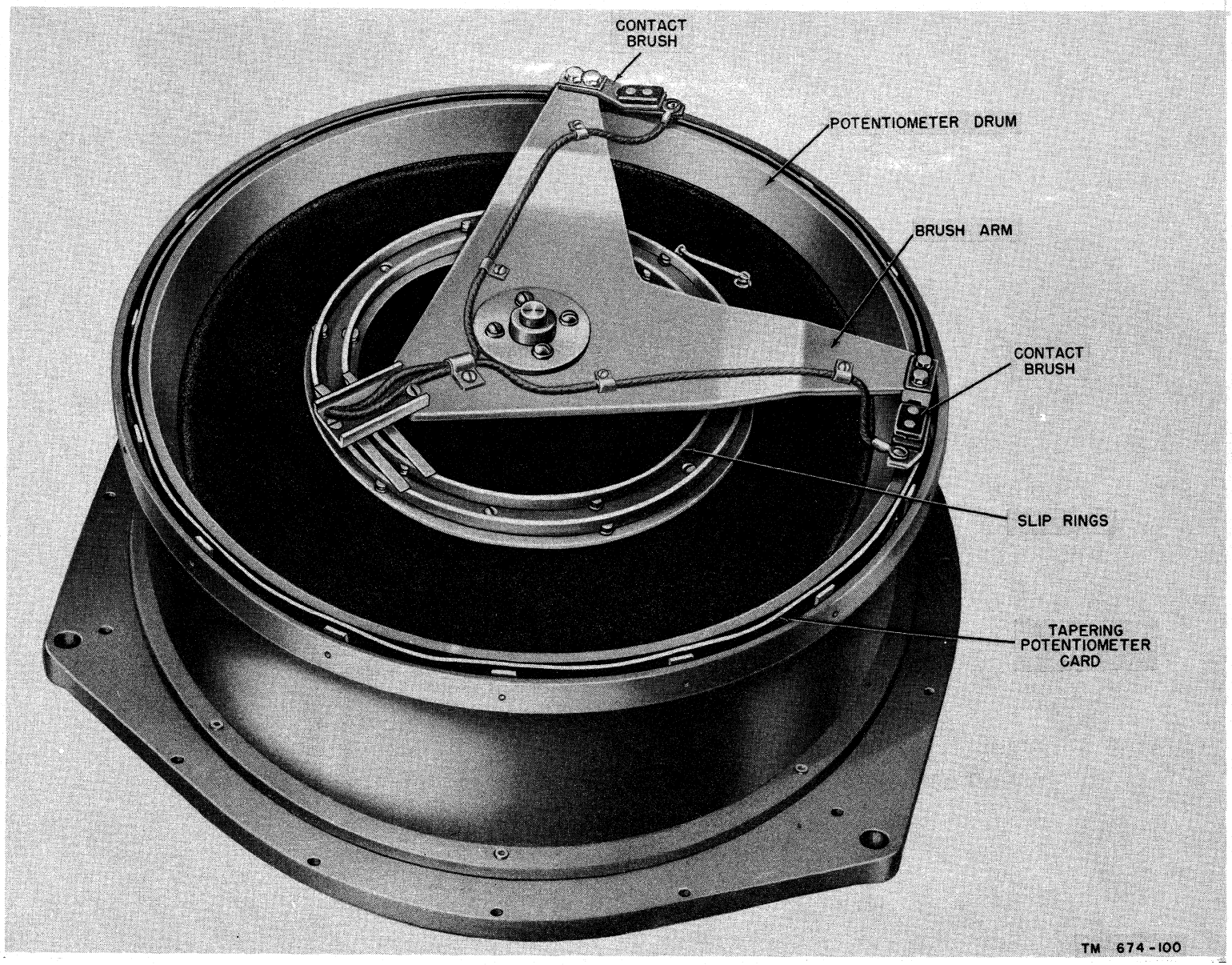


Figure 106. Typical nonlinear potentiometer.

movable sliding contacts. In the conventional type (A of fig. 105) the resistance wire is wound on an insulating strip called a resistance card. The card is bent so that it forms an arc of nearly 360°, and is mounted so that the slider makes contact with the winding along one edge of the strip. The slider usually is able to rotate continuously, but it loses contact with the resistor over a small arc. In servo usage, the potentiometer should be thought of as a variable-voltage source rather than as a variable resistor, in that an input voltage is applied to the resistance element, and a fraction of this voltage appears as output between the slider and one end of the resistance. Unfortunately, the output of a potentiometer does not change smoothly as the slider is moved. Instead, the output voltage changes in jumps, each jump being equal to the voltage difference existing between adjacent turns of wire. A potentiometer having 1,000 turns of wire on the resistance element is said to have a resolution of 1 part in 1,000 or a resolution of .1 percent, which means that the smallest change in the output voltage is 1/1,000 of the input voltage.

b. In order to improve the resolution (make the voltage jumps smaller), the resistance element sometimes is wound in a helix as shown in the helipot in B of figure 105. The slider may make as many as 10 turns in covering the whole element, and although this construction allows many more turns on the resistance element, it suffers from the disadvantage that the slider cannot rotate continuously. Since the change in voltage along the resistance element is proportional to the change in resistance, it is simple to make a nonlinear potentiometer by using a nonuniform resistance card. Figure 106 shows a typical nonlinear potentiometer, in which the output voltage is proportional to the sine of the angle through which the potentiometer shaft is turned. Where the card is narrow, the resistance between two adjacent points on the winding is low, and the voltage changes slowly with slider motion. Where the card is wide, the length of wire in each turn is greater, the resistance is higher, and the voltage changes more rapidly. Such a potentiometer provides a cosine output if zero position for the shaft coincides with the point where the positive voltage is applied. If this is called the 90° position, the output will be proportional to the sine of the shaft angle. Since either sine or cosine output may be obtained by proper choice of zero position, potentiometers of this sort are called *sine-cosine potentiometers.*

87. Potentiometers for Data Transmission

Since a linear potentiometer develops an output voltage proportional to its shaft angle, it frequently is used as part of a data-transmission system. The rate servo discussed in paragraphs 27 through 34 operates by matching the output voltage of a tachometer against an external speed order in the form of a voltage. The speed-order voltage may be obtained conveniently from a potentiometer by using a fixed excitation and setting the shaft to an angle corresponding to the desired speed. It is possible also to use a potentiometer to control a positioning servo. The position order is set on a potentiometer shaft, and the output voltage is sent to the servo as a position order. A follow-up potentiometer at the servo develops an output voltage proportional to the actual position, and the difference between the two potentiometer outputs is the error voltage. This method is not desirable, however, because the limited resolution of the follow-up potentiometer causes the servo to behave like an on-off servo for small errors, and it hunts back and forth between positions corresponding to adjacent turns of the resistance element. The difficulty may be overcome by a device called an induction potentiometer (par. 89). A potentiometer can be used also as part of a simple remote indicator. If a potentiometer is set by a shaft, the output voltage can be sent to a voltmeter and the meter reading will indicate the position of the shaft. The principal merit of this arrangement is that a d-c power source can be used, whereas an a-c power source is required for the more precise synchro indicator. The chief liability of the potentiometer as a remote indicator lies in the fact that the potentiometer output is proportional to both the shaft setting and the input voltage. Unless the input remains constant, the system will not be free from error. It is nevertheless used frequently where precise indication is not necessary.

88. D-C Synchro

The d-c synchro (fig. 107) is an improvement on the potentiometer-voltmeter remote indicator, and it also operates on direct current. It is, however, not affected by small changes in the level

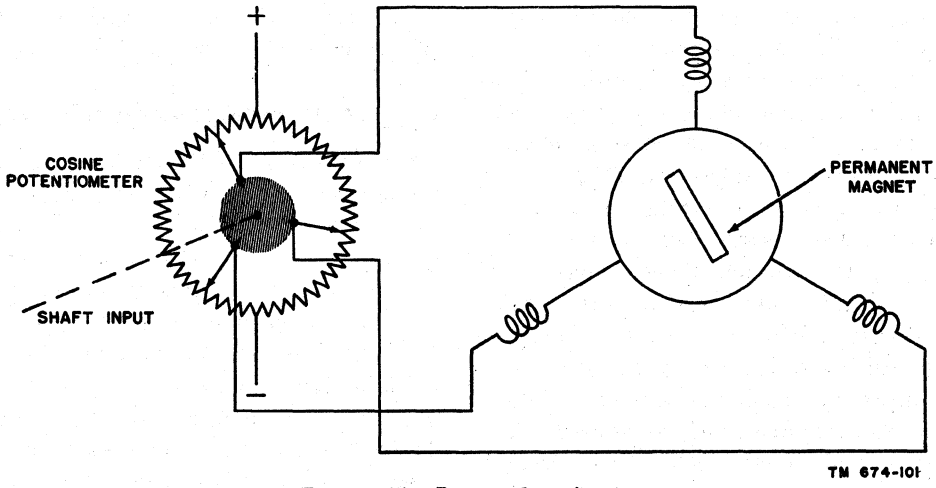


Figure 107. D-c synchro circuit.

of the d-c supply. The transmitting element is a sine-cosine potentiometer with three sliders spaced 120° apart. The three output voltages are similar to those of a synchro transmitter except that they are d-c rather than a-c voltages. The receiving element consists of three stator coils and a permanent magnet rotor. The three voltages cause currents to flow in the windings, and these set up a magnetic field with which the rotor alines itself. Systems of this sort frequently are used where a-c power is not available, but whenever a-c is available, synchros are preferred.

89. Induction Potentiometer

The induction potentiometer is similar to a synchro or a resolver, but has only a single rotor winding and a single stator winding. By shaping the pole pieces, it is possible to make the output voltage of such a unit proportional to the shaft angle rather than the sine of the shaft angle over a limited range. The induction potentiometer is more complicated than a conventional potentiometer and can be used only on a-c. Its merit lies in the fact that it has higher resolution than most wire-wound potentiometers.

Section VIII. OTHER SENSING ELEMENTS

90. Microsen

The microsen (fig. 108) is used occasionally as an induction potentiometer. Its chief merit is that there are no electrical connections to the rotor and consequently there are no brushes. The magnetic field of the input windings magnetizes the iron rotor, and the magnetic field of the iron rotor induces voltage in the output windings unless the rotor is in its zero position. Over a limited range, the output voltage is proportional to the displacement of the rotor. The microsen, like other magnetic elements, requires a-c.

91. E-Transformer

The E-transformer (fig. 109) sometimes controls a positioning servo. Alternating current is applied to the input coil on the center leg of the core. When the armature is in its zero position, the mag-

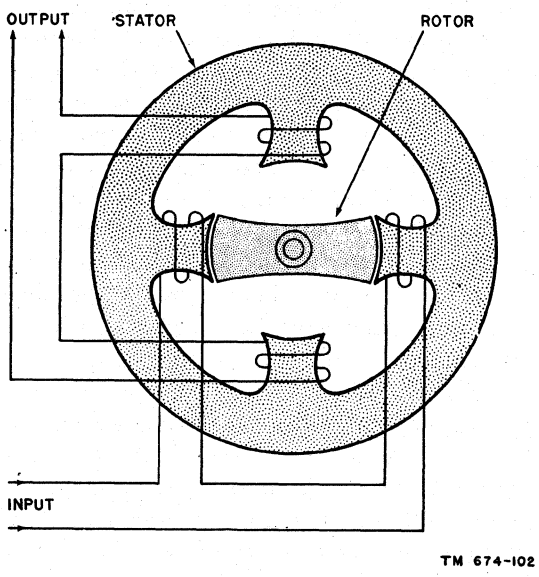


Figure 108. Microsen circuit.

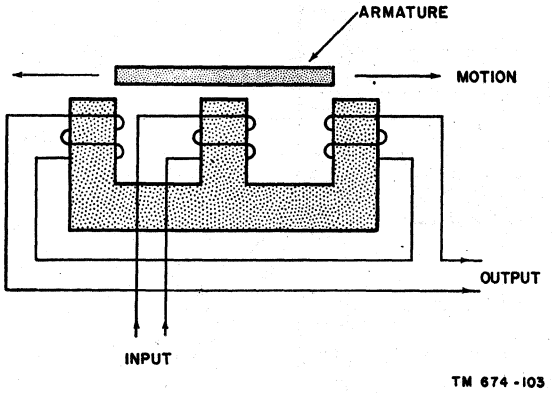


Figure 109. E-transformer circuit.

netic field of the input coil is split evenly between the two outer legs, and the voltages induced in the two output coils are equal. The coils are connected so that the two voltages oppose each other, and the net output is zero. When the armature is displaced, more of the field passes through one of the outer legs than through the other. The voltage induced in one output coil therefore rises, the voltage in the other coil falls, and the output is no longer zero. Over a reasonable range, the output voltage is proportional to the displacement of the armature, being in phase with the input for displacements in one direction, and being 180° out of phase with the input for displacements in the other direction. The E-transformer is useful when a servo positions one mechanical part so that if follows the motion of another part. One part then carries the armature, the other part carries the core, and the servo drives the follower part to a position for which the transformer output is zero.

92. Linear-Control Transformer

A linear-control transformer (fig. 110) is much

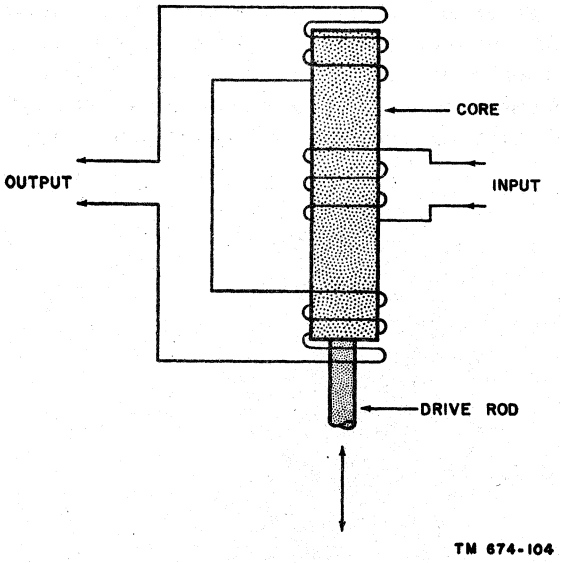


Figure 110. Linear-control transformer circuit.

the same as an E-transformer, except that the moving element is a short core which moves inside the three windings. With the core in the center position, the voltages induced in the two output windings are equal and the output is zero. Over a reasonable range of core movement, the output is proportional to the core displacement.

93. Contact Head

The contact head is described briefly in paragraph 14*a* as a sensing element for an on-off servo. Because of a number of possible mechanical modifications of the contact head, including double contacts, small displacements produce small error voltages and large displacements produce large voltages. Most servos, however, are proportional and do not use contact sensing elements.

Section IX. OTHER ELEMENTS

94. Mechanical Damper

A mechanical damper (fig. 111) is a flywheel coupled to a shaft through friction disks. When the shaft turns at constant speed, or is stationary, the flywheel acts as though it were fixed to the shaft. When the shaft is accelerated, the flywheel does not change its speed at once. It therefore exerts a torque, through the friction disks, which opposes the acceleration. Its chief application is in synchro receivers, where it provides acceleration damping and prevents spinning at synchronous speed.

95. D-C Generator

As a separate component, a small d-c generator, called a tachometer generator, frequently is used as a rate follow-up, and also to provide a viscous damping voltage. The usual d-c generator for ap-

plications of this sort uses a permanent magnet field and is designed to deliver an output voltage proportional to its speed of rotation. Such a d-c generator, which is designed for precise output, is called a tachometer or a tachometer generator.

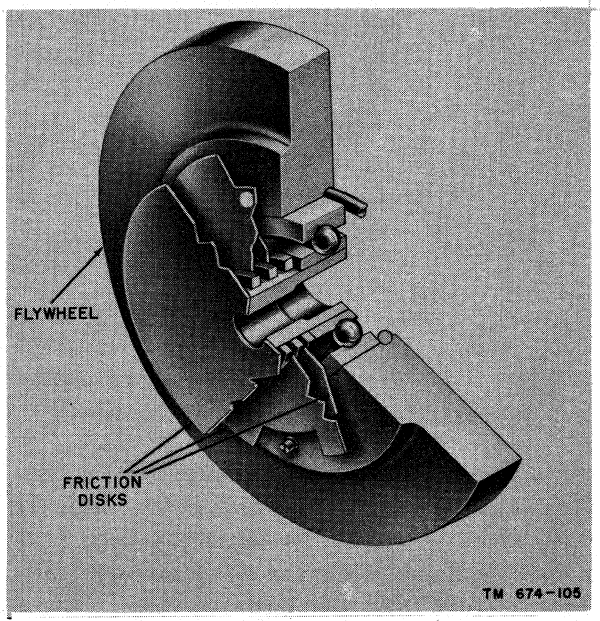


Figure 111. Mechanical damper.

96. Induction Generator

The tachometer generator provides a d-c output proportional to its speed of rotation, and is used as a rate follow-up and to provide a viscous damping signal for d-c servos; for a-c servos, the induction generator (fig. 112) serves the same purpose. The usual a-c generator, or alternator, delivers an output in which both the amplitude and the frequency are proportional to shaft speed. This obviously is not suitable for use in an a-c servo, since it is not permissible to use anything but the normal operating frequency. The induction generator, however, delivers an output proportional to its shaft speed, which has a fixed frequency, and which reverses its phase when the direction of rotation is reversed. The theory of the induction generator is relatively simple. The excitation coils, which are energized with a-c at the operating frequency, produce an alternating magnetic field. When the rotor turns, voltage is induced in it and current flows. The voltage and consequently the current are proportional to the rotor speed and also to the magnetic field. Since the magnetic field alternates, the rotor voltage and current alternate as well. The magnetic field of

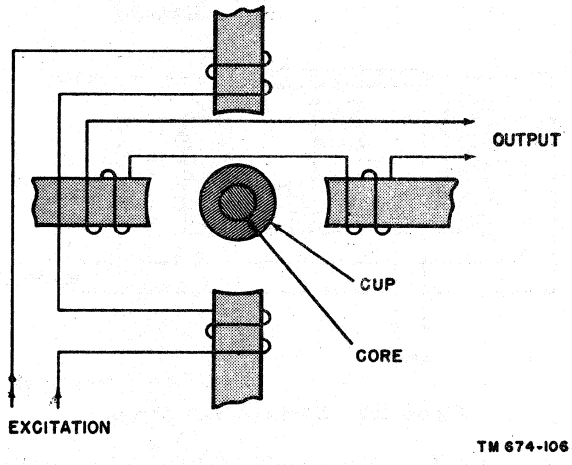


Figure 112. Induction generator circuit.

the rotor current induces voltage in the output windings.

97. Acceleration Generator

An acceleration generator is physically the same as an induction generator, but it is excited with d-c instead of a-c. As before, the rotor current is proportional to the magnetic field and to the rotor speed. In the acceleration generator, the excitation is d-c and the magnetic field is fixed. The rotor current therefore is fixed for any given shaft speed. Since a steady magnetic field does not induce voltage, there is no output when the shaft speed is constant. If the shaft speed changes, however, the rotor current and its accompanying magnetic field also change, and the changing field induces a voltage in the output windings. The output is a d-c voltage proportional to the rate at which the shaft speed is changing, having one sign for speed changes in one direction, the opposite sign for changes in the other direction. The principal application of the acceleration generator is to provide an acceleration damping signal for a d-c servo. If acceleration damping is required for an a-c servo, an acceleration generator may be used with any of the modulators described in paragraph 60.

98. Mechanical Integrator

A mechanical integrator is nothing more than a variable-speed drive. The input shaft turns a disk, and this drives the output shaft. In A of figure 113, the output shaft is driven through a small wheel which rides on the disk. In B, the bevel gear connected to the output shaft is driven

by the balls in the ball cage. For a given speed of the disk and input shaft, the speed of the output shaft is proportional to the radius at which the wheel or the ball cage is set. Over a period of time, the total turns of the output shaft are proportional to those of the input shaft times the average value of the radius. If, for example, the radius is set to be proportional to speed and the input shaft is driven at a constant rate, the total turns of the output shaft will be proportional to distance. Two such integrators, the radius of one set proportionally to north-south speed and the radius of the other set proportionally to east-west speed, will give continuous computation of distance north and distance east from a starting point.

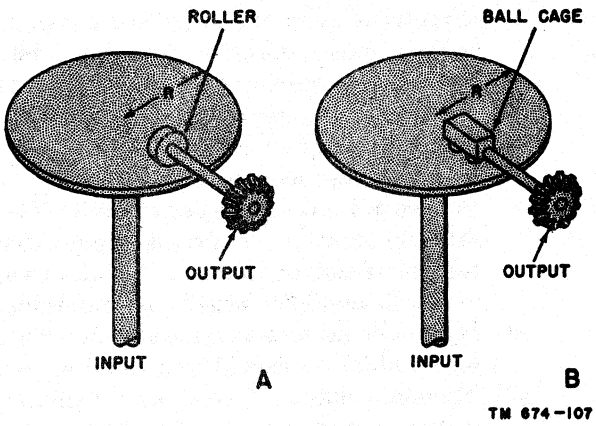


Figure 118. Mechanical integrator.

Section X. GENERAL CONSIDERATIONS

99. Combinations of Elements

No rules can be given regarding the possible combinations of elements in a servo system. In general, choice is dictated by power level, but it may be governed also by availability of power sources, size, weight, and so on. For example, the a-c signal from a synchro control transformer may be amplified in a vacuum-tube amplifier, rectified in a phase-sensitive detector, and passed as direct current to a saturable reactor which controls a high-power a-c motor. Alternatively, the d-c may be used as input to a d-c amplifier which drives the field of an amplidyne or a Ward-Leonard drive. In still other cases, the synchro signal may be amplified and used to run a small induction motor which operates the control valve for a heavy hydraulic ram. Most computing servos, however, operate from synchros or resolvers, using vacuum-tube amplifiers and small induction motors.

100. D-C and A-C Systems

D-c systems are preferable in two respects—high torque is more readily obtainable with d-c motors than with a-c motors, and precision rate signals are more easily obtainable from tachometer generators than from induction generators. The two major difficulties with d-c systems are, first, the problem of obtaining great amplification and, second, the problem of establishing zero. Both of these difficulties disappear in a-c systems, and for this reason a-c servos normally are used unless torque requirements dictate the choice of d-c motors, much of the servo being operated as an a-c system.

101. Summary and Review Questions

a. Summary.

(1) D-c motors are used commonly as actuators in servos driving heavy loads, since they develop higher stall torque than a-c motors, and also where a-c in large amounts is not readily available. Control by variation of the armature voltage normally is preferred to control by variation of field voltage. In low-power servos, split-field d-c motors frequently are used.

(2) Many servo systems have a-c induction motors. For low-inertia applications, as in computing servos, cup rotors are preferable, although rotors sometimes are more efficient.

(3) Hydraulic actuators frequently are used, particularly in aircraft systems. A hydraulic accumulator provides energy for a swash-plate motor or hydraulic ram. Solenoid actuators and microsen restraint motors prove efficient in military servo systems.

(4) Backlash in actuators may be minimized by the preloading motors or, more commonly, by split gearing.

(5) Modified Ward-Leonard and amplidyne drives are efficient as controllers for certain high-power d-c motors.

(6) D-c motors may be controlled by the

thyratrons by means of a-c error signals without phase-sensitive detection. For a-c motors requiring only small amounts of power on the control field, vacuum-tube circuits are suitable.

(7) For large a-c motors, when time lag of the control current is not objectionable, saturable-reactor or magnetic-amplifier control is not uncommon. Of the two, magnetic amplifier usually is preferable.

(8) Hydraulic valves may serve as controllers, operated by a solenoid or a small motor,

(9) Magnetic-clutch drives or steel-tape drives may serve as combination actuators and controllers.

(10) Many servo systems require modulators, such as mechanical choppers, various vacuum-tube circuits, or rectifier modulators. For developing a d-c output from an a-c input, commutators may be synchronous mechanical switches, vacuum-tube circuits, or rectifier commutators.

(11) For many applications, variable-gain amplifier circuits are desirable.

(12) Transfer circuits switch control from coarse to fine sensing elements. Relay circuits are not as common as vacuum-tube and rectifier circuits. A small bias voltage may be added to the output of synchros used as sensing elements, the sum of the output voltage and the bias voltage serving as the error signal.

(13) Most high-performance servos utilize error-rate damping networks and integrating networks.

(14) The mechanical differential is the basic sensing element for comparing two mechanical positions which are in the form of shaft settings. In servos using electrical error signals, vibrating-reed comparators, differential amplifiers, parallel-addition and series-addition circuits serve as voltage-comparison sensing elements.

(15) A synchro transmitter converts shaft data to synchro data, which positions the synchro receiver shaft in accordance with that of the transmitter. Synchro receivers are used generally as remote indicators.

(16) A synchro control transformer develops an output voltage equivalent to the difference between its actual shaft position and that called for by synchro data. It combines the functions of data receiver, follow-up, and sensing element.

(17) A synchro differential transmitter develops synchro data equivalent to the sum or difference of its inputs, which are both mechanical and electrical. A synchro differential receiver is connected to two syncho transmitters, and sets its shaft to the difference between the transmitted shaft angles. It normally is used as a remote indicator.

(18) All elements of synchro data-transmission systems must be synchronized. Normally, each component is adjusted individually. Certain standard designations and connections normally are followed for all similar equipment.

(19) Resolvers serve as coordinate converters in computers. To provide greater precision, booster amplifiers are frequent. Resolvers and boosters are used occasionally for data transmission.

(20) Potentiometers and d-c selsyns sometimes serve as remote indicators when precise indication is not necessary and when the use of a d-c power source is desirable. Induction potentiometers, which have higher resolution than wire-wound units, sometimes are used when an a-c power source is available. Microsens serve often as induction potentiometers, since there are no electrical connections to the rotor.

(21) E-transformers and linear-control transformers frequently control positioning servos, especially in applications where one mechanical part must follow the motion of another part.

(22) Synchro receivers often have mechanical dampers providing acceleration damping and preventing synchronous spinning.

(23) Tachometer generators provide viscous damping and serve as rate follow-ups for d-c servos. Induction generators are used in a-c servos and, excited by direct current, provide acceleration damping.

(24) Mechanical integrators can provide continuous mechanical computation of changing values.

(25) In general, a-c servo systems are more practical than d-c systems; however, for applications in which high torque is required, d-c components may be efficient.

b. Review Questions.

(1) Why are d-c motors usually preferred to a-c motors?

(2) How can backlash be minimized in actuators?

(3) Name two drivers commonly used for high-power d-c motors?

(4) What is mechanical differential?

(5) Explain the use of a synchro.

(6) Give the common voltages and frequencies used by synchros.

(7) What is meant by resolution in a wire-wound potentiometer?

(8) Name the three types of potentiometer.

(9) Why are booster amplifiers used?

(10) When are mechanical dampers used in synchro receivers?

(11) What can be used as a substitute for an induction potentiometer? Why?

(12) Is an a-c servo system more practical than a d-c system? Give at least three reasons.

CHAPTER 4

EXAMPLES OF SERVOS AND SERVO SYSTEMS

Section I. AUTOMATIC TEMPERATURE-CONTROL SERVO SYSTEM

102. Description

One example of a servo system is an automatic oil-burning furnace operating under the control of a thermostat. It is designed to maintain an even temperature in a house when the outdoor temperature is lower than the desired indoor temperature. The house is heated by turning on the furnace; since the outdoor temperature is lower than the desired indoor temperature, the house is cooled by turning off the furnace. The furnace is automatic in the sense that it may be turned on and off by closing and opening a single external switch, and the thermostat controls it in this way. The several operations involved in turning on the furnace, such as turning on the blower which delivers air, turning on the oil stream, and lighting the oil, are carried out in proper sequence under the control of automatic mechanisms in the furnace and need not be considered in this discussion.

103. Operation as Servo System

Since the complete system controls the temperature of the house, and operates in response to any difference between the actual temperature and the desired temperature, it is effectively, a servo system (fig. 114). The thermostat, acting as a sensing element, controls the furnace, which is the actuator of the system. When the temperature becomes too low, the furnace is turned on, and the temperature of the house is raised immediately. When the temperature is too high, the furnace is turned off, and the house is cooled as quickly as possible. The complete system is therefore an on-off servo operating without any dead space.

104. Thermostat

A thermostat (fig. 115) consists of a strip formed of two different metals, one of which expands and contracts more than the other when the temperature is changed. It is the sensing element of the servo system. At some specific temperature, the strip is straight. At higher temperatures, the strip is bent in such a way that the metal which expands more is on the outside of the arc (which is longer than the inside), and at lower temperatures it is bent in the opposite direction. This thermostat strip acts as the temperature follow-up (fig. 114). The temperature order is set into the system by adjusting the position of a fixed electrical contact which acts as one side of the furnace-control switch. The other side of the switch is a moving contact carried on the thermostat strip as shown in figure 115. When the temperature is too low, the switch is closed; when the temperature is too high, it is opened. The sensing element (the thermostat) has no dead space. That is, it does not recognize the possibility of a correct temperature but sees all temperatures as either too low or too high.

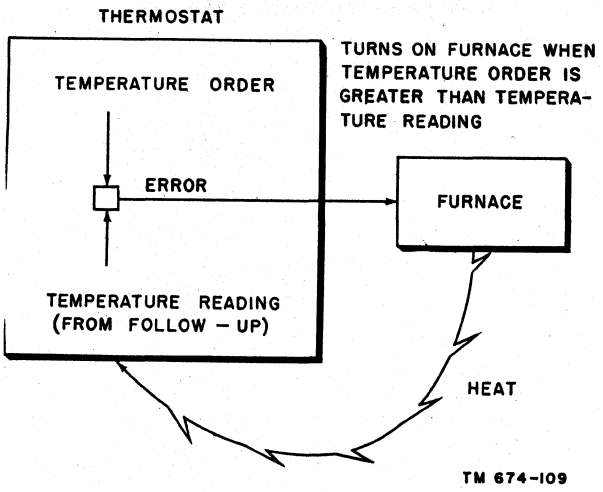


Figure 114. Automatic temperature-control system operation as a servo system.

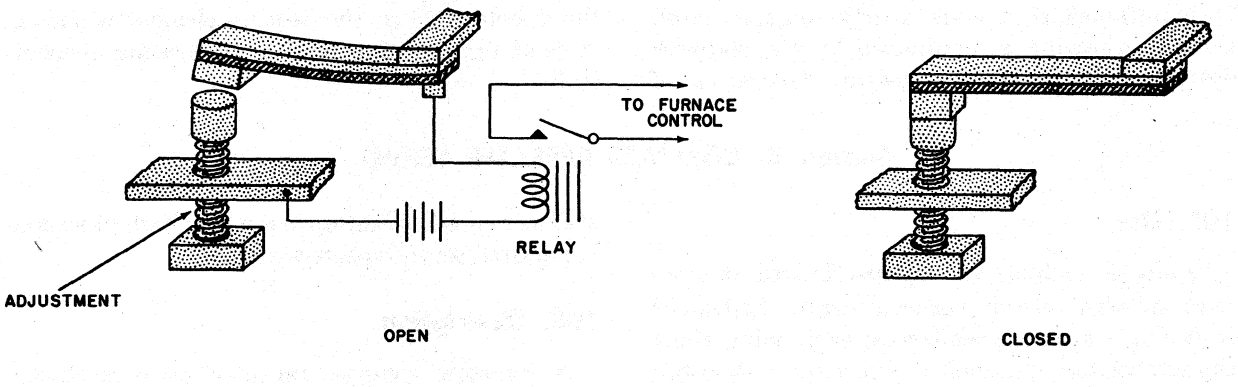


Figure 115. Thermostat operation.

105. System Behavior

Like any other on-off servo without sufficient dead space, the system oscillates (or hunts) back and forth about the desired temperature. Although there is no momentum, as in a mechanical positioning servo, the system coasts past the desired point. When the house is cooling, the furnace is turned on as soon as the temperature is too low, but it does not give off heat immediately and the temperature continues to drop for some time after the thermostat switch is closed. Similarly, after the switch is opened, the furnace continues to give off heat and the temperature continues to increase for some time.

106. On-Off to Stepwise Conversion

The system can be converted to stepwise operation in the direction of heating by adding a small heating element (fig. 116). The heating element is controlled by the thermostat switch and is located near the thermostat strip. When the switch contacts close, the heating element immediately begins to heat the thermostat strip. It therefore causes the switch to open again after a short interval, and the duration of this interval is proportional to the amount by which the house temperature is too low. As soon as the strip cools, the switch contacts close again, and the stepping cycle is repeated. This enables the house temperature to

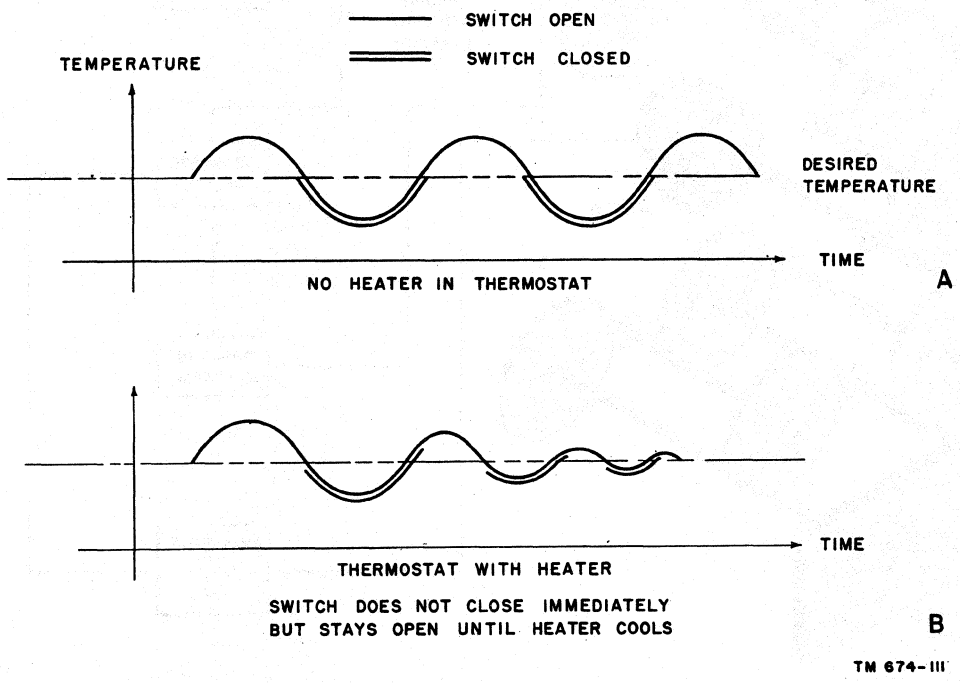


Figure 116. Operation of temperature-control system as on-off servo and as stepwise servo.

be maintained at a more nearly constant level, since overheating is minimized by the stepwise operation of the control system. Operation of the system without the heating element is shown in A of figure 116, and with the heating element in B.

Section II. COMPASS REPEATER SERVO

107. Use

Compass readings usually are desired at more than one point on a ship or an aircraft. Instead of installing a separate compass at each point where the information is needed, it is customary to install a single master compass of high precision. The reading of this compass then is repeated elsewhere by a sensitive servo follower using the E-transformer described in paragraph 91, or some similar device, as a sensing element. The servo sets coarse and fine synchro transmitters, so that the compass reading is available in the form of synchro data. At points where the compass reading is required with only low precision, synchro receivers are used as remote indicators, but where high precision is required servo repeaters are used.

108. Description

A complete compass repeater servo is shown schematically in figure 117. The incoming information arrives on eight wires. Three wires carry coarse synchro data, three carry fine synchro data, and two carry a reference a-c voltage that excites the synchro transmitters. The coarse synchro transmitter operates at 1-speed, making one revolution for 360° change in the compass reading. The fine synchro transmitter operates at 36-speed, making 36 revolutions for 360° change in the com-

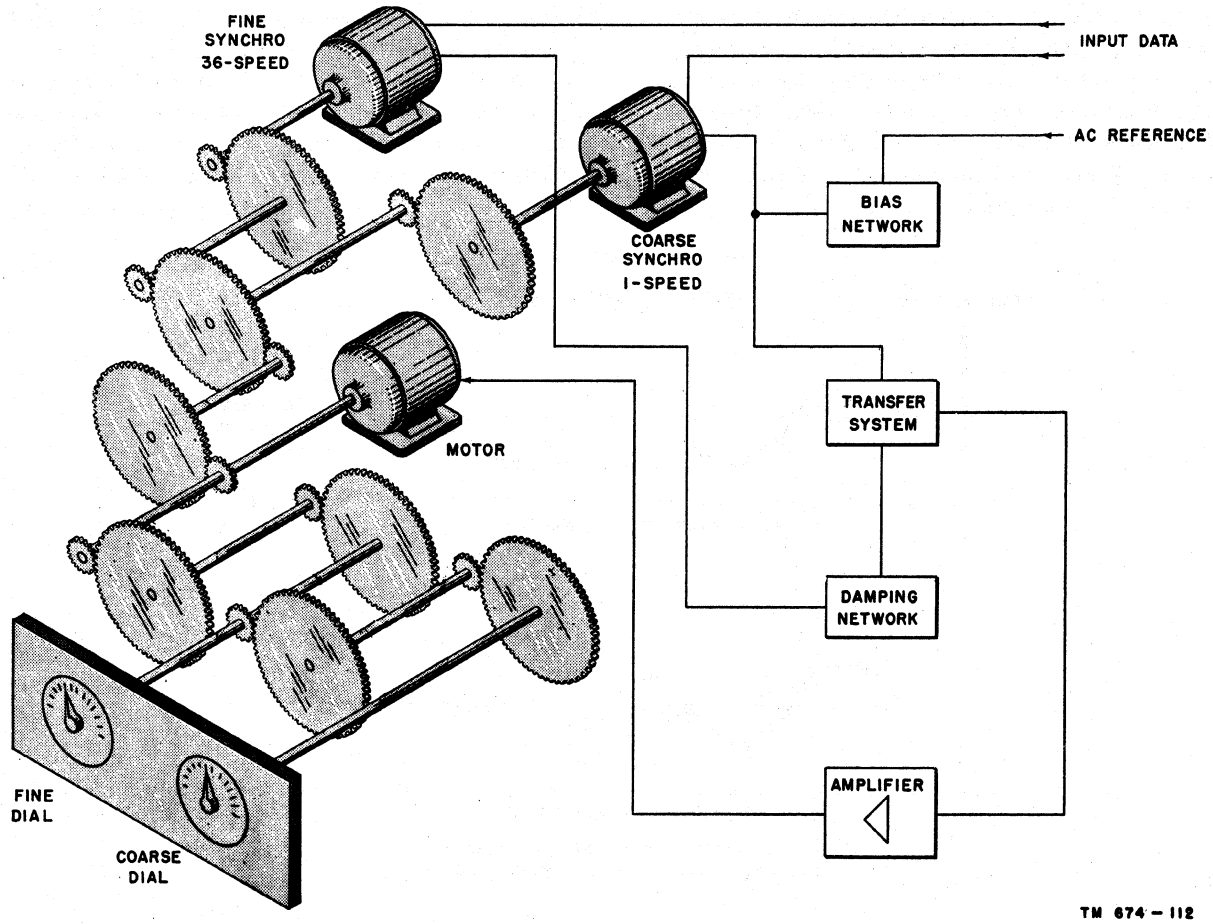


Figure 117. Compass repeater servo.

pass reading, or one turn for a change of 10°. The coarse synchro control transformer in the repeater operates at the same 1-speed as the transmitter to which it is connected. Similarly, the fine synchro control transformer operates at the same 36-speed as the fine transmitter. The two synchro outputs are sent to a transfer circuit, and the output of this circuit feeds a vacuum-tube amplifier which drives one field of a small servo motor. The reference a-c voltage provides excitation for the other field of the servo motor, and also provides a bias signal which is added to the output of the coarse synchro before it is sent to the transfer circuit. A damping network is connected between the fine synchro and the transfer network. Since the servo is undamped while it is under control of the coarse synchro, it approaches its proper position at the greatest possible speed. As soon as control is transferred to the fine synchro, the damping network provides critical damping and the dials are positioned without overshoot.

Section III. ANTIAIRCRAFT TRACKING RADAR

109. Spherical Coordinates

The position of a target in a plane can be described by two coordinates. These may be, for example, Cartesian coordinates (distance north and distance east) or polar coordinates (range and bearing). When the target is not confined to a plane, three coordinates are required to specify its position. In terms of Cartesian coordinates, these may be distance north, distance east, and height, or distance up. The first two coordinates may be converted to polar form so that the coordinates become horizontal range, bearing, and height. Height and horizontal range then may be converted to polar form (fig. 118), to obtain slant range and elevation. The three coordinates—azimuth (or bearing, if the reference direction is north), elevation, and slant range—are called spherical coordinates.

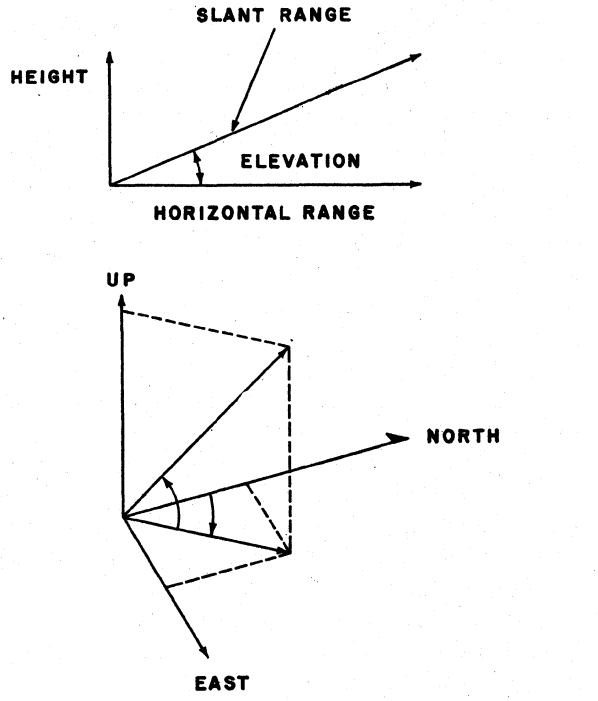


Figure 118. Spherical coordinates.

110. Conical-Scan Radar

The antiaircraft radar described below tracks a selected target automatically, keeping its antenna pointed in the proper direction without assistance from the operator. The direction in which the radar antenna points is called the radar line of sight. The radiated beam is strongest in a direction called the beam axis. By movement of the antenna-feed system in respect to the reflector, the beam axis is made to rotate around the radar line of sight, the angle between the beam axis and the radar line of sight being held constant. Each point on the beam axis thus describes a circle whose center lies on the radar line of sight, and the beam axis moves around the surface of a cone whose axis is the radar line of sight. This radar is called a conical-scan radar because the beam sweeps (or scans) a conical volume of space. This is shown in figure 119, where the circle is the path described by a point on the beam axis. When the radar tracks a target, the antenna is positioned by two servos so that the target lies on the radar line of sight (which is the axis of the cone). A cutaway view of the servo system which controls the antenna for a conical-scan radar is shown in figure 120.

a. Theory of Operation. A radar consists of a transmitter, a receiver, and various indicators and servos which make use of the receiver output.

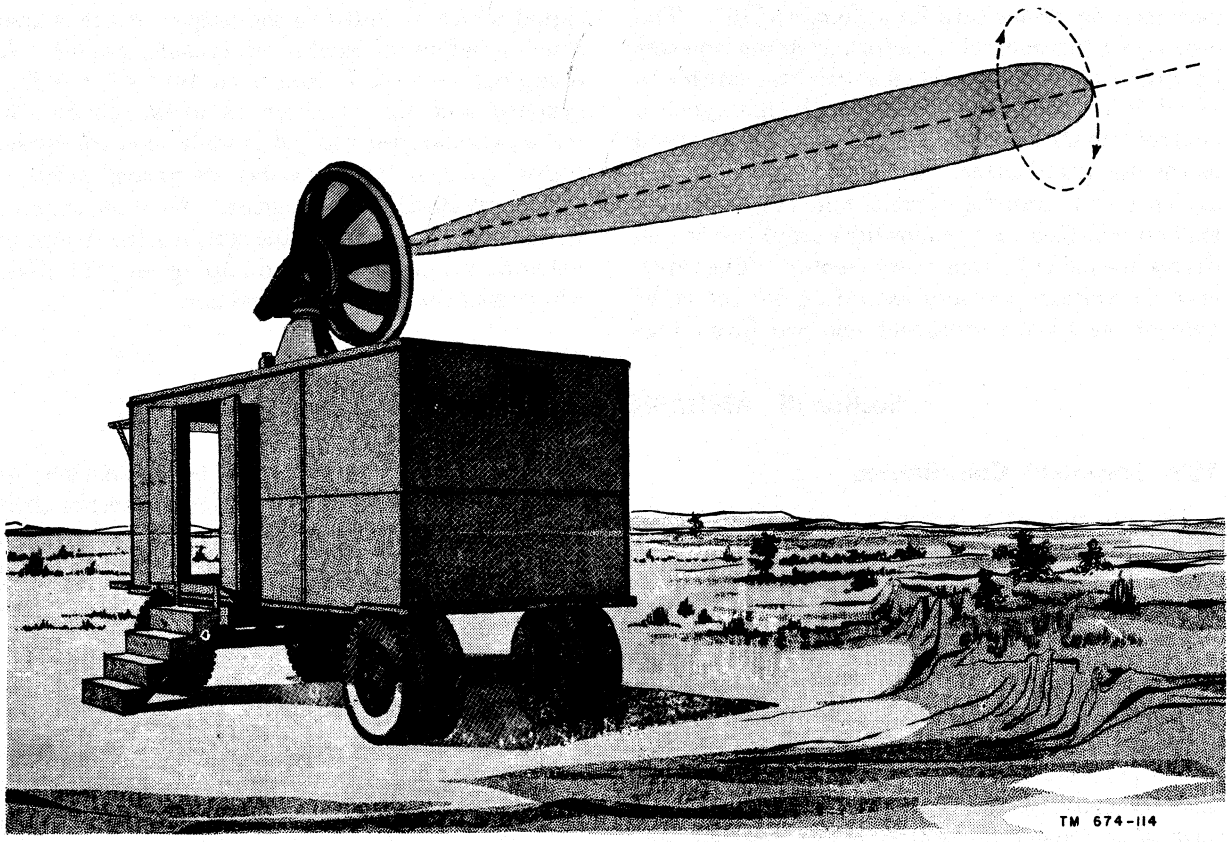


Figure 119. Conical-scan radar.

The transmitter is designed to deliver short pulses, each lasting about 1 microsecond (one-millionth of a second). If there is a target in the radiated beam, some of the transmitted energy will be reflected and picked up by the receiver, which normally uses the same antenna as the transmitter. Since radio waves travel approximately 330 yards in 1 microsecond, the echo from a target at a range of $165t$ yards will arrive t microseconds after the transmitted pulse. Other things being equal, the strength of the echo is greatest when the target lies somewhere on the beam axis. The range of a target is determined by noting the time interval between transmission of the outgoing pulse and receipt of the echo, and the direction can be obtained by noting the antenna position for which the echo is strongest. Since the transmitter delivers something like 400 pulses per second, the information is available continuously.

b. Range-Gate Echo Selection. Echoes are received from all targets in the transmitted beam every time the radar sends out a pulse. It is possible, however, to select the echoes from a single target by means of a range gate. Since the tracking servos operate on the basis of information contained in the radar receiver output, it is necessary to exclude all signals except those from the target that is being tracked. The receiver output is passed to an amplifier which normally is cut off so that it delivers no output. The signal which causes the transmitter to deliver a pulse is also passed to a unit called a range-gate generator, and this delivers an output pulse after an interval (which may be varied) of t microseconds. The output pulse of the range-gate generator, which is called the range gate, turns on the amplifier for a short period. If there is a target at a range of $165t$ yards, its echo will arrive at the amplifier just as it is turned on by the range gate. The amplifier output then consists solely of the echoes from targets (if there are any) in the transmitted beam at a range of $165t$ yards. In general, there will be only one target (or no target) in the beam at any given range. The use of a range gate, therefore, allows selection of the echoes from a single target so that the echo

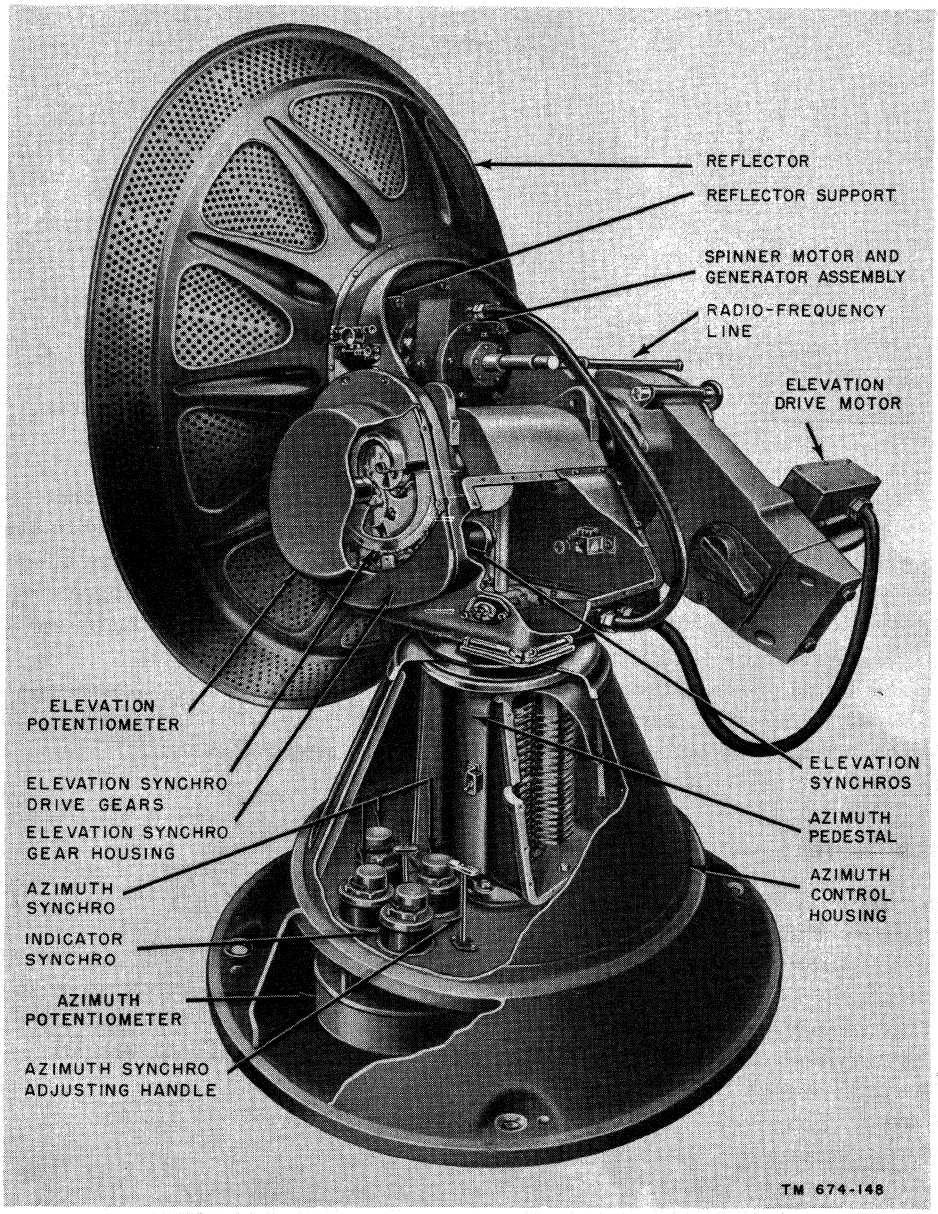


Figure 120. Conical-scan antenna.

strength of that target can be measured easily without interference.

c. Conical Scanning. As explained above, the beam axis of the transmitted beam does not coincide with the radar line of sight. The angle between them, however, is constant, so that a target lying on the radar line of sight will return an echo of constant strength. The echo will vary as the aspect and range of the target change. It will not, however, vary appreciably during one scanning period, which is normally 1/30 second. If the target is slightly off the radar line of sight—for example, above it—the echo will be strongest when the beam axis lies above the radar line of sight and weakest when the beam axis lies below. The echo strength then will vary at 30 cps (cycles per second). The echoes from the selected target can be filtered to obtain a varying voltage proportional to the echo strength. This will have a d-c component proportional to the average echo strength and an a-c component at 30 cps proportional to the variation in the echo strength during

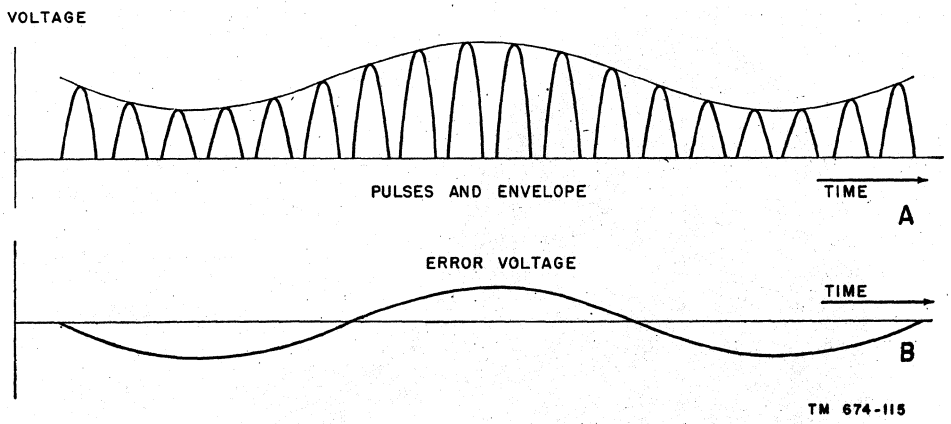


Figure 121. Echo pulses and error-voltage waveforms.

each scanning cycle. The amplitude of the a-c component indicates the *amount* by which the target is off the radar line of sight, and the phase of the a-c component indicates the *direction* in which the target is off. If the radar is pointed below the target, for example, so that the target lies above the radar line of sight, the a-c component of the filtered voltage will have a positive peak at the instant when the transmitted beam lies above the radar line of sight.

111. Antenna Servo Signals

If the target lies on the radar line of sight, the voltage obtained by filtering the pulses will not vary appreciably during one scanning cycle. If, on the other hand, the target is not on the radar line of sight, the voltage will have a 30-cps component. This component, called the *error voltage*, controls the two servos which position the antenna.

a. Error-Voltage Waveform. The output of the gated amplifier (the amplifier that is turned on by the range gate pulse) is a series of pulses which appear at the same rate as the transmitted pulses and which have varying heights (A of fig. 121). These pulses are passed through a filtering circuit, similar to the detector of an ordinary radio, to obtain the 30-cps component of the envelope of the pulse heights. This signal is the error voltage, shown in B. The d-c component of the filter output, which is proportional to the average pulse height, is used as an automatic-gain control voltage for the radar receiver. This varies the receiver gain in such a way as to hold the average pulse height nearly constant for different average echo strengths. The use of automatic-gain control makes the error voltage for a given pointing error independent of the average echo strength (which varies with both range and target size). The level of the 30-cps signal then depends only on the pointing error, or the angle between the radar line of sight and a line joining the antenna to the target.

b. Error-Voltage Commutation. The conical scan is produced by moving the antenna-feed mechanism at a 30-cps rate. The shaft that drives

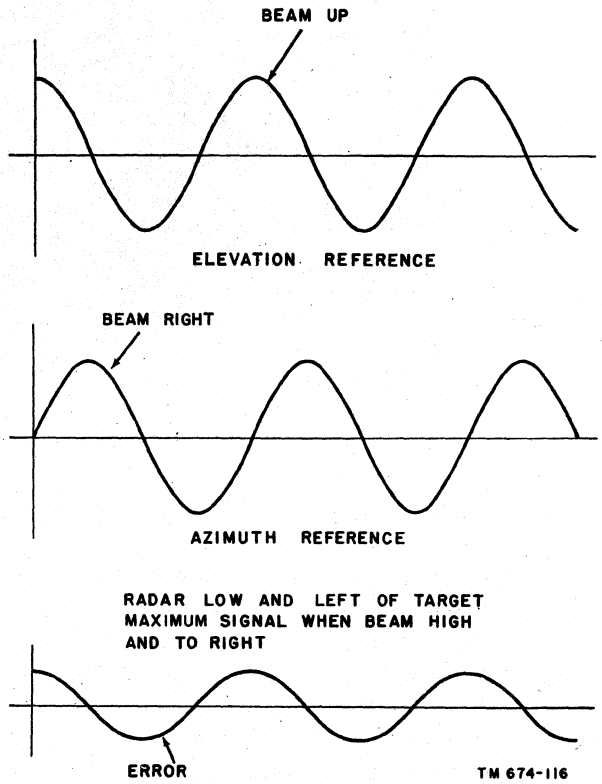


Figure 122. Reference and error voltages phase relationship.

the feed mechanism also drives a small two-phase a-c generator. One output voltage, called the elevation reference voltage, is phased so that it reaches a positive peak when the beam axis lies above the radar line of sight. The other output voltage, called the azimuth reference voltage, reaches a positive peak when the beam axis lies to the right of the radar line of sight. The 30-cps error voltage is fed to two commutator circuits, one using the elevation reference voltage for switching, the other using the azimuth reference voltage. These are usually vacuum-tube commutators (fig. 60) which, besides commutation, provide some amplification. The output of the elevation commutator is a polarized d-c voltage which is, for example, positive if the radar is pointing low (if the target is above the radar line of sight) and negative if the radar is pointing high. The output of the azimuth commutator is positive if the radar is pointing to the left and negative if it is pointing to the right. The outputs of the two commutators act as error voltages for the elevation and azimuth servos that position the antenna. In each case, the error voltage (the commutator output) is proportional to the difference between the actual angle—elevation or azimuth—and the desired angle. Figure 122 shows the relative phases of the elevation reference voltage, the azimuth reference voltage, and the error voltage. The case chosen is one in which the radar is pointing below and to the left of the target. The target then lies above and to the right of the radar line of sight and the positive peak of the 30-cps error voltage occurs between the positive peaks of the two reference voltages.

112. Antenna-Positioning Servo Systems

The d-c output of each commutator is passed to a d-c amplifier which excites the field of an amplidyne. The amplidyne output then feeds the armature of a high-power d-c servo motor which positions the antenna through a gear train. Except as noted below, both servos are identical. A complete antenna-positioning servo system is shown in figure 123.

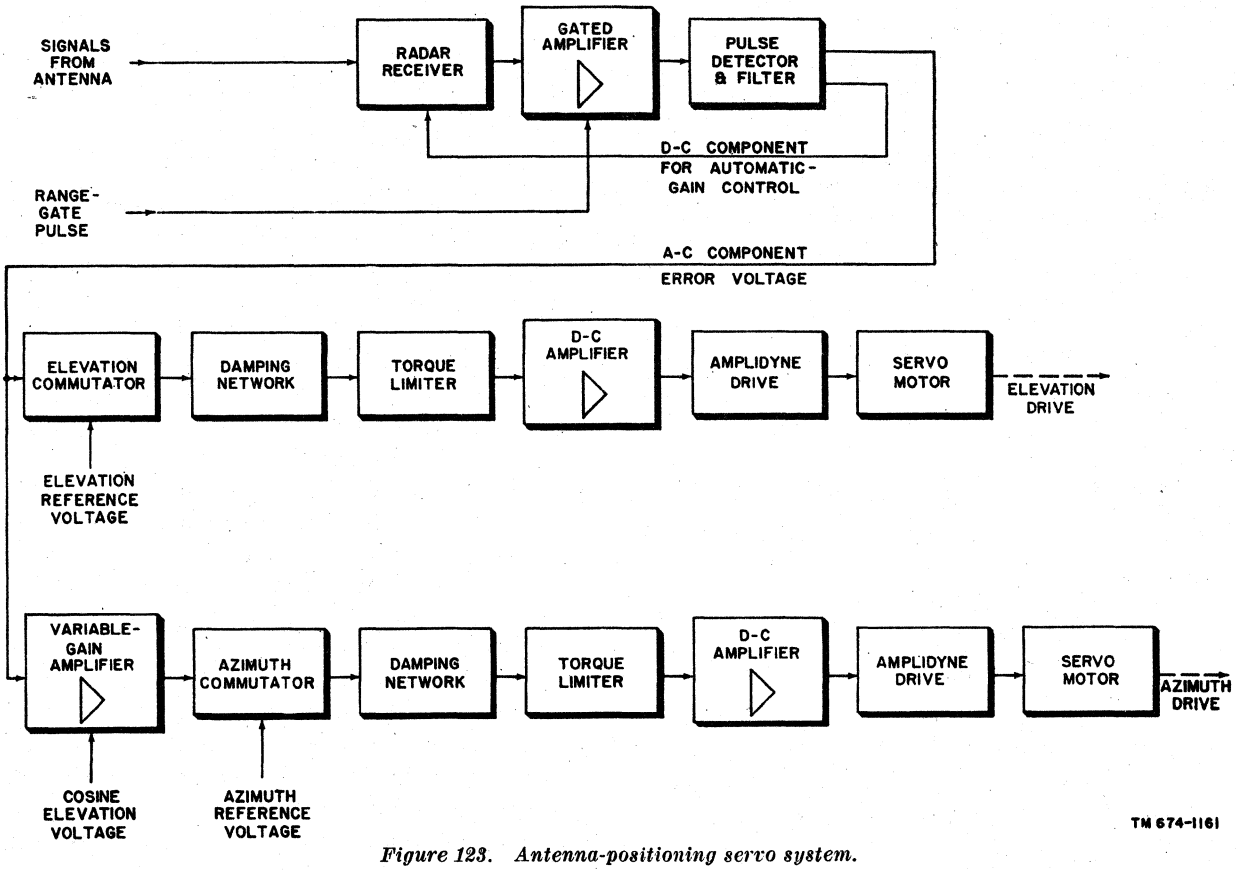


Figure 123. Antenna-positioning servo system.

a. Reason for Choice of Amplidyne Drive and D-C Servo Motor. The amplidyne drive is chosen as the simplest controller for a high-power d-c motor. It is desirable to use a d-c motor because of its high stall-torque characteristic. This is required because the antenna structure is fairly heavy, and also because the motor may be called on to deliver stall torque for relatively long periods while it holds the antenna motionless against a wind.

b. Elevation Servo. The elevation servo (fig. 123) is a simple device. The output of the elevation commutator is passed to a d-c damping network so that the servo may be damped without imposing any velocity lag. The output of the damping network then passes to a torque limiter consisting of a pair of rectifiers and resistors (fig. 124). For small signals, the rectifiers, which are usually crystal rectifiers rather than vacuum tubes, have high resistance, and the signal is passed with little attenuation. For higher signals, the rectifier that is passing current has a low resistance, and the circuit acts as a voltage divider. The circuit, therefore, acts as a limiter and cannot deliver more than some predetermined maximum output. The torque limiter feeds a d-c amplifier (fig. 123) which controls an amplidyne, and the amplidyne drives the d-c servo motor which changes the antenna elevation. Because of the torque limiter, the servo motor cannot deliver more than a predetermined torque, and thus it is impossible for the mechanical parts of the antenna and the drive

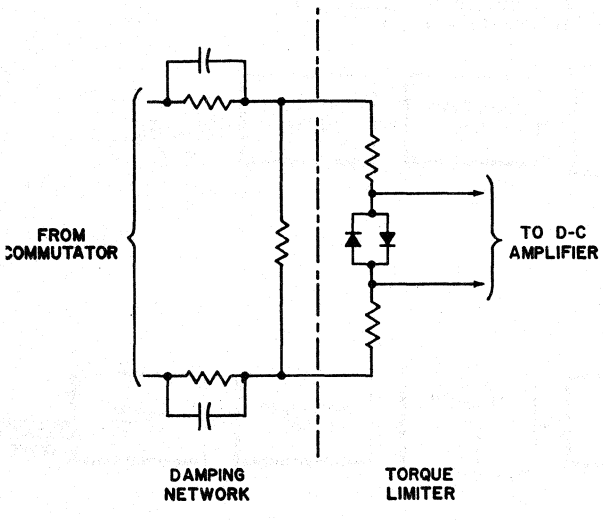


Figure 124. Balanced damping network and torque-limiter circuit.

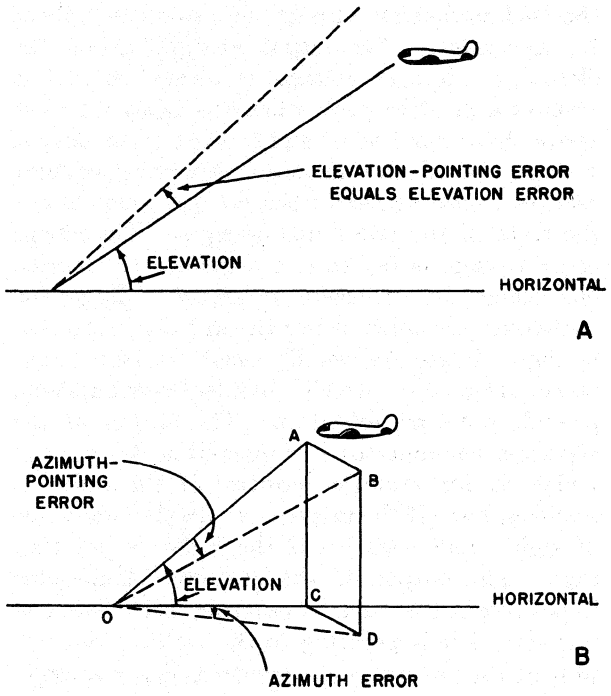


Figure 125. Relationship between antenna-position error and pointing error.

to be damaged by an excessively large error signal.

c. Azimuth Servo. The azimuth servo (fig. 123) differs from the elevation servo by having a variable-gain amplifier ahead of the commutator. The control signal for this is proportional to the cosine of the elevation angle, and is obtained from a resolver or a sine-cosine potentiometer excited by a constant voltage and driven mechanically by the elevation gearing of the antenna. The effect of the variable-gain amplifier is to divide the error voltage by the cosine of the elevation angle. A of figure 125 shows that a given elevation error always will produce a pointing error equal to the elevation error. The output of the elevation commutator is then always proportional to the elevation error and the elevation servo operates in a proportional manner. This is not true for an error in azimuth. As shown in B, the pointing error resulting from a given azimuth error is different for different elevation angles. The ratio CD/CO is the sine of the azimuth error, but for small errors this may be taken as equal to the azimuth error in radians. The azimuth-pointing error is equal to AB/AO, or CD/AO, since AB and CD are equal. A given azimuth-pointing error must then

be multiplied by AO/CO to obtain the azimuth error (since CD/AO times AO/CO is equal to CD/CO), or divided by CO/AO. However, CO/AO is precisely the cosine of the elevation angle; the 30-cps error signal is, therefore, divided by the cosine of the elevation in the variable-gain amplifier, and the output of this is fed to the azimuth commutator. With this arrangement, the output of the azimuth commutator is always proportional to the azimuth error, and the servo operates as a proportional servo with the possibility of critical damping at all elevation angles.

113. Synchro System

The arrangement of servo components shown in figure 126 illustrates the extreme adaptability and complexity of servo systems in general. The arrangement is an experimental one, used for testing various combinations; it does not represent a specific application. As shown, it is an indicating

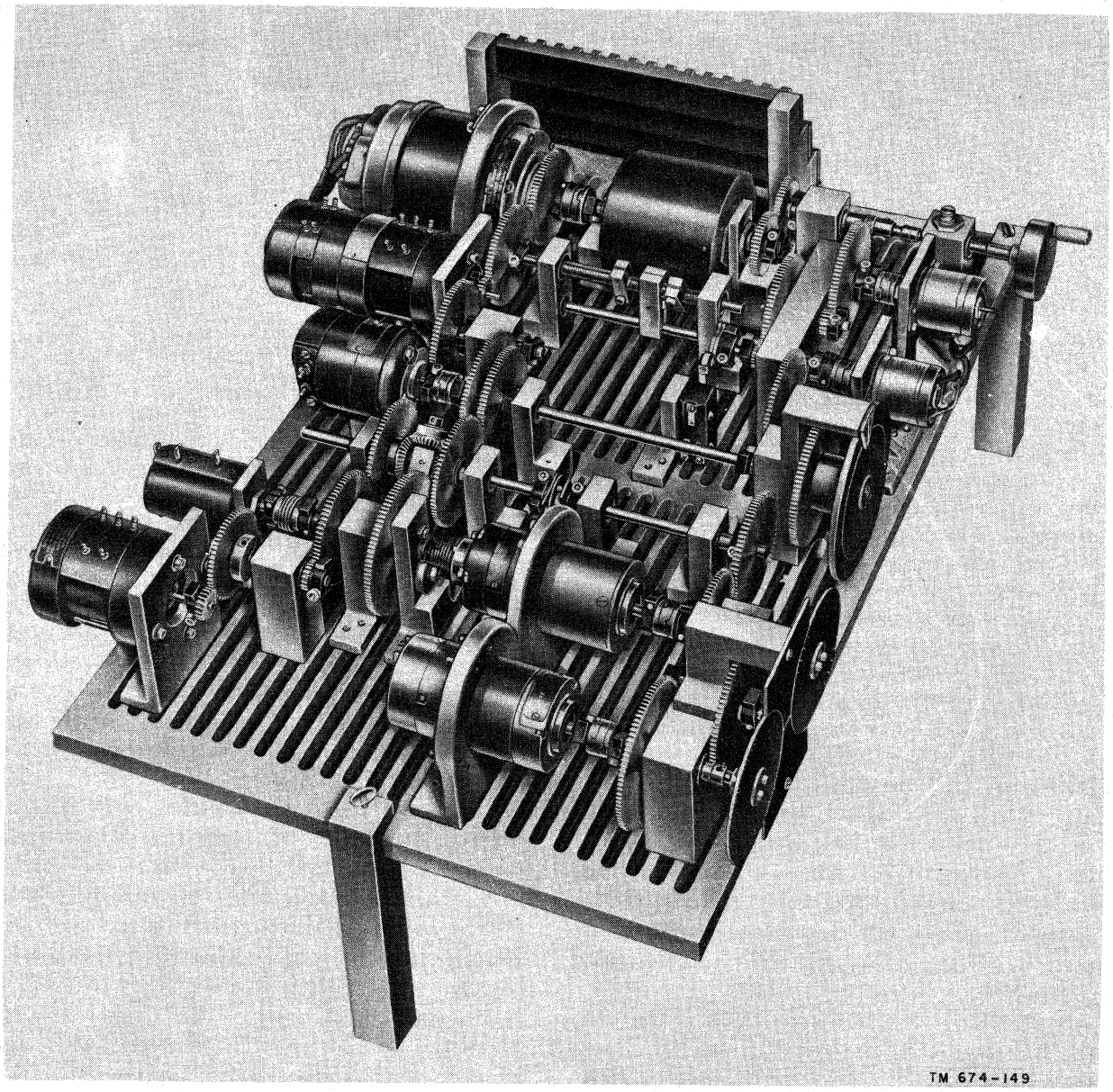


Figure 126. Experimental servo system.

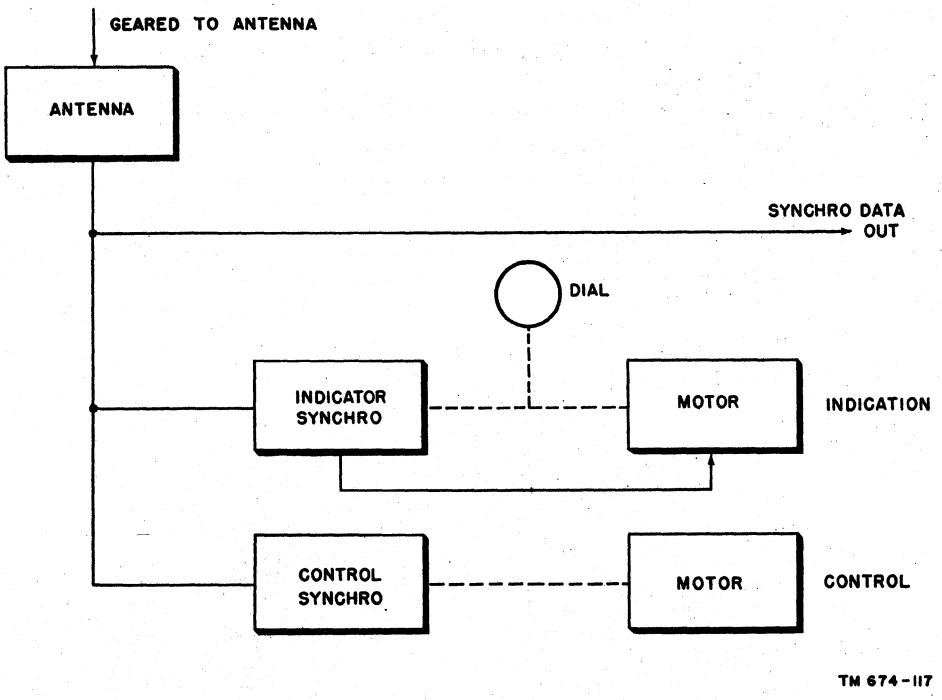


Figure 127. Synchro system

servo. Data may be set mechanically by a handwheel; potentiometer dials indicate developed values. The components shown, such as d-c motors, synchro transmitters, receivers, and control transformers, mechanical and electrical switches, are discussed in chapter 3. A fairly elaborate system of synchros is required in order that the position of the antenna may be sent to the predictor when the radar is tracking a target; the antenna position may be controlled by an operator when the radar is searching for a target; and the antenna may be remotely controlled to place it on a target which has been picked up by an optical tracking system. Figure 127 has been simplified by showing only the coarse synchros, although such a system normally has both coarse and fine synchros at each of the three positions. The complete synchro system, with six synchros and two motors in addition to the antenna positioning motor, is duplicated for elevation and azimuth, but since both systems operate in the same way, the following discussion covers both.

a. Tracking Connections. During tracking, the antenna-positioning servo acts in response to the error voltage obtained from the radar receiver. The antenna synchros are connected as transmitters and send synchro data out on the synchro busses. The indicator synchros operate as control transformers and control the indicator servo motor which sets dials that show the antenna position. The transfer network, damping network, bias system, and amplifier are omitted from figure 127. The control synchros, whose purpose is explained in *b* below, are also connected as control transformers and control their own servo motor which positions them. During tracking, the antenna is positioned automatically in response to signals developed by the radar. The indicator dials and the control synchros follow the antenna position. The synchro busses carry the antenna position, as synchro data, to points outside the radar.

b. Manual-Control Connections. For manual control, the control synchros are connected as synchro transmitters. The servo motor associated with the control synchros is used by the operator to position them, the control of the motor being effected by a manually operated potentiometer. The antenna synchros are connected as control transformers, and their output, after passing through a transfer network, is passed to the appropriate commutator, which is supplied with synchro excitation voltage (in place of the 30-cps reference voltage) for switching. The control syn-

chros are positioned manually by the operator and everything else follows them. The antenna is positioned by its servo to follow the control synchros. The indicator synchros set the dial to agree with the control synchros and, therefore, with the antenna position. The synchro busses carry information from the control synchros, which have the same position as the antenna, to points outside the radar. Since the control synchros are held in synchronism with the antenna during tracking, there will be no sudden shift in antenna position when the system is switched to manual control.

c. Remote-Control Connections. For remote control, the antenna synchros are connected as for manual control, and the control synchros are connected as in automatic tracking. Everything then follows the external synchro data. The control synchros are held in synchronism with the antenna, as in automatic tracking, so that the system can be switched to manual control without any shift in antenna position.

Section IV. ANALOGUE COMPUTATION

114. Digital and Analogue Computers

Calculating equipment, or computers, are used in connection with many parts of gunnery, with torpedo and depth-charge equipment, and for the solution of mathematical problems connected with navigation. These are representative uses, but do not even begin to cover all the military applications of computers. Suppose, to use a simple example, that it is necesary to add two numbers, each being a digit less than 10. Let the numbers be 3 and 5. One way of doing this is to use a mechanical counter. The counter can be set initially at zero. It is then set forward three steps, and after that five more steps. It will, of course, read 8. Another method is to use a pair of potentiometers and connect them across 10-volt sources. One can be adjusted to provide an output of 3 volts and the other can be set for an output of 5 volts. The two outputs then can be added electrically and measured with a voltmeter. At first glance, there is nothing to recommend either method. The second method, however, has decided advantages if the two numbers are replaced by 346 and 519. In the first method, it is necessary to provide a counter with more stages and then to carry out a large number of operations. For example, all the stages of the counter are set to zero at first, and the first operation is to move the last stage forward six steps, and then nine. The last stage now reads 5, and has also set the next stage forward to 1, so that the last two stages read 15, which is the sum of 6 and 9. Now, 4 and 1 are set into the second stage which reads 6. Then 3 and 5 are set into the first stage, and the total may be read as 865. This is a long process. With potentiometers, however, it is necessary only to provide finely calibrated dials against which the pointers of the adjusting knobs are read. These dials are set to provide outputs of 346 volts and 519 volts, and the sum is read as before on a voltmeter. The first method of computation is known as a digital method, since all operations are on the numbers themselves. The second method is called analogue computation, since voltages are used as the analogues of the numbers. Shaft rotations, displacements of rods, or almost any physical quantities may be used in place of voltages. In general, when the computation is required with a precision of .1 percent or less, analogue computation is preferred as cheaper and simpler. When higher precision is required, a digital computer is used. Analogue computers use large numbers of servos to set the physical quantities involved.

115. Multiplication by Analogue Computer

Suppose it is necessary to multiply two quantities, Y and Z. This problem can be written as $X=YZ$. Assume that both Y and Z are positive, and that neither exceeds 10. This is carried out conveniently as an analogue computation, using three potentiometers and one servo as shown (fig. 128). The first potentiometer is used to develop a voltage proportional to Y. If the potentiometer is connected across a 10-volt source, its maximum output will be 10 volts, which will be equal to the largest value of Y. If the shaft of the potentiometer then is set to an angle corresponding to Y (one-quarter of the way from the bottom for Y equals 2.5, for instance) the output will be a voltage that is numerically equal to Y. This is used to excite the second potentiometer, which has its shaft set at a position proportional to Z. The output of the second potentiometer is proportional

to its input voltage and to its shaft setting, or proportional to YZ. In order to find the scale factor, or the constant of proportionality, note that the maximum output of the second potentiometer for a given setting of the first is Y volts. This, however, corresponds to a Z-setting of 10 and an output of 10Y. The output of the second potentiometer is then YZ on a scale of .1-volt per unit, since the maximum output of 10 volts represents an X value of 100. The value of X represented by the voltage of the third potentiometer, which is the value set on the shaft, is compared with the output of the second potentiometer, which is the voltage corresponding to YZ as given by the shaft settings of the first and second potentiometers. If the X-setting is correct, the X-voltage will be equal to the YZ-voltage. If not, the two voltages will be different, and when one is subtracted from the other there will be a nonzero error voltage proportional to the error in the X-setting. This is used to control the servo motor which changes the setting of the third potentiometer. Although this example is simple, it is a good illustration of the way in which an analogue computer works.

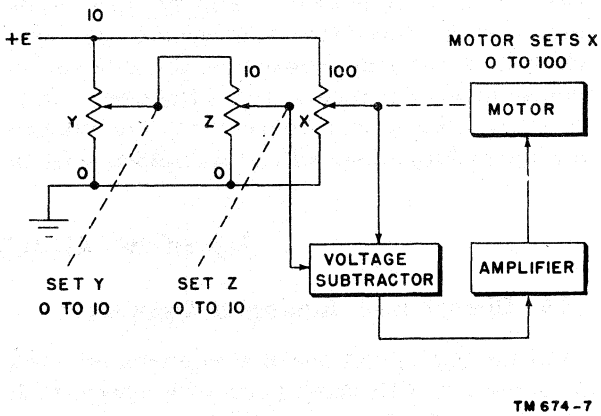


Figure 128. Analogue multiplication.

Section V. ANTIAIRCRAFT PREDICTOR

116. Antiaircraft Prediction Problem

An antiaircraft predictor receives continuous inputs of target position data as range, azimuth, and elevation. By using the target position and velocity, it determines a future target position suitable for the guns with which it is associated. The future target position is one at which the guns can hit the target. That is, shells aimed at the future target position and fired at the present moment will arrive there at the same time as the target (fig. 129).

117. Input Data

The predictor receives present values of slant range, angle of elevation, and azimuth as coarse and fine synchro data from the radar. In each case, the synchro data are converted to a shaft position by an input servo which is nothing more than a repeater servo, similar to the one described in paragraph 108. All of the repeater servos are identical, with the single exception that they may use different coarse-fine ratios. Figure 130 shows an input servo in schematic form.

118. Position-Data Conversion

To determine the future target position, the predictor must know the velocity of the target in addition to the position. Although this can be found directly from the spherical position coordinates, it is more convenient for the purpose of this discussion to assume that the predictor converts the position data to Cartesian coordinates and then determines the target velocity. In the discussion in *a* and *b* below, it is assumed that the azimuth angles are measured in respect to north; they are, therefore, referred to as bearings.

a. Conversion From Slant Range and Elevation to Horizontal Range and Height. A voltage proportional to present slant range is obtained from a potentiometer that is set by the present range shaft and excited by a fixed voltage (fig. 131). The potentiometer output, the present slant-range voltage, feeds a booster amplifier which excites a resolver. The shaft angle of the resolver is set by the present-elevation shaft. The two resolver outputs are voltages proportional to present height and present horizontal range.

b. Conversion From Horizontal Range and Bearing to Distance North and Distance East. The present horizontal range voltage feeds a booster amplifier which excites a resolver, the shaft of the resolver being set by the present-bearing shaft (fig. 132). The outputs of the resolver are voltages proportional to present distance north and present distance east.

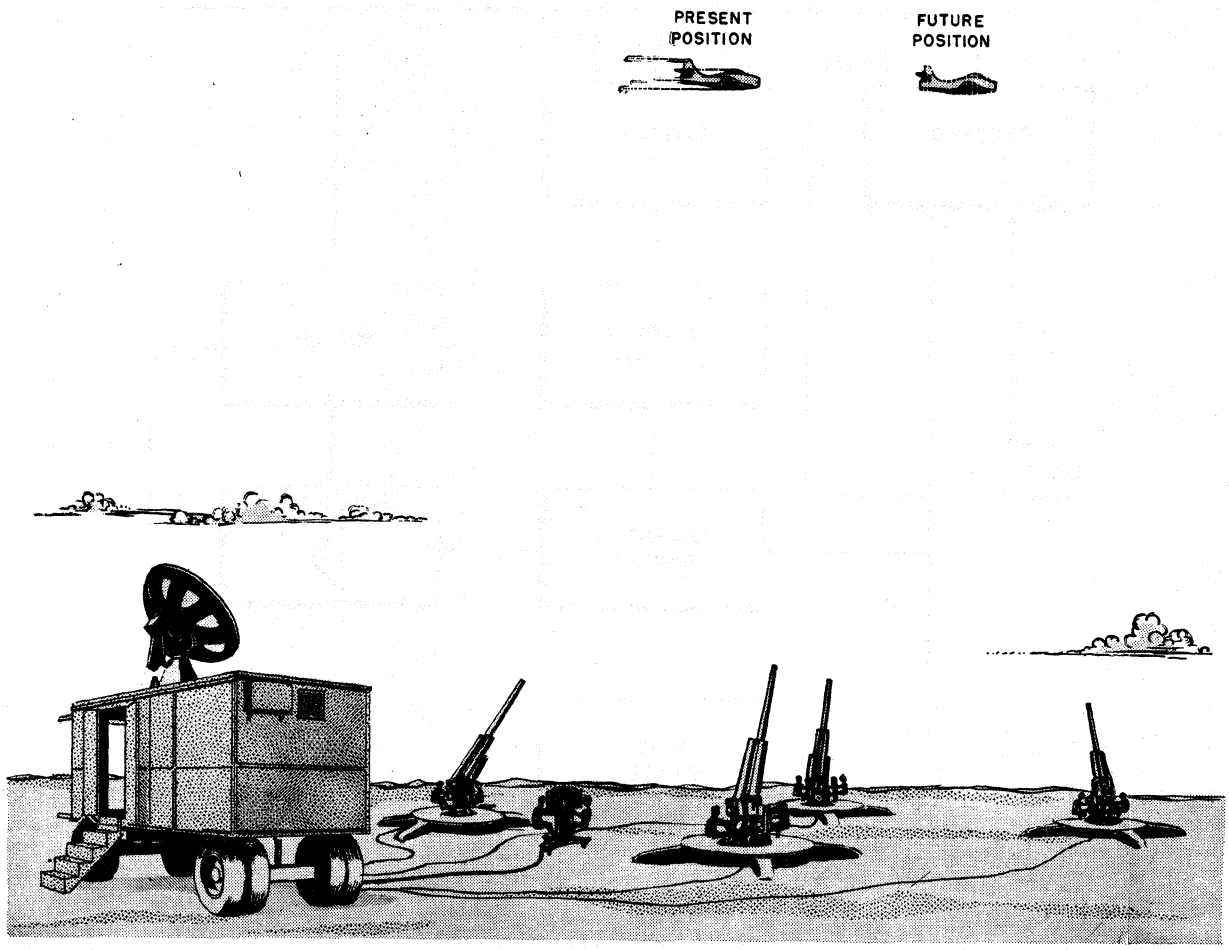


Figure 129. Antiaircraft prediction problem.

119. Voltage to Shaft Conversion

The conversion is carried out in each case by a servo (fig. 133), all of the servos being the same. A standard voltage feeds a booster amplifier, and this excites an induction potentiometer. The output of the induction potentiometer is matched against the coordinate voltage, and the difference is the error voltage for a servo which positions the induction potentiometer and the coordinate shaft.

120. Development of Cartesian Rates

The three rates, north speed, east speed, and upward speed, are developed as voltages by induction generators. These have constant excitation voltage and are driven by the shafts which are set to the present Cartesian coordinates.

121. Cartesian Coordinates

Cartesian coordinates of the future target position relative to the tracking device may be found by adding displacements to each of the three Cartesian coordinates. Each displacement is found by multiplying the Cartesian rate by a time called the displacement time, the product of rate and time being the displacement distance, or simply the displacement. However, it is necessary to know the future target position in respect to the gun position rather than in respect to the position of the tracking radar. This is obtained by adding parallel distances to the sum of the present coordinates and the displacement distances. In each case, the parallax distance is the distance between gun position and radar position, measured from the gun position.

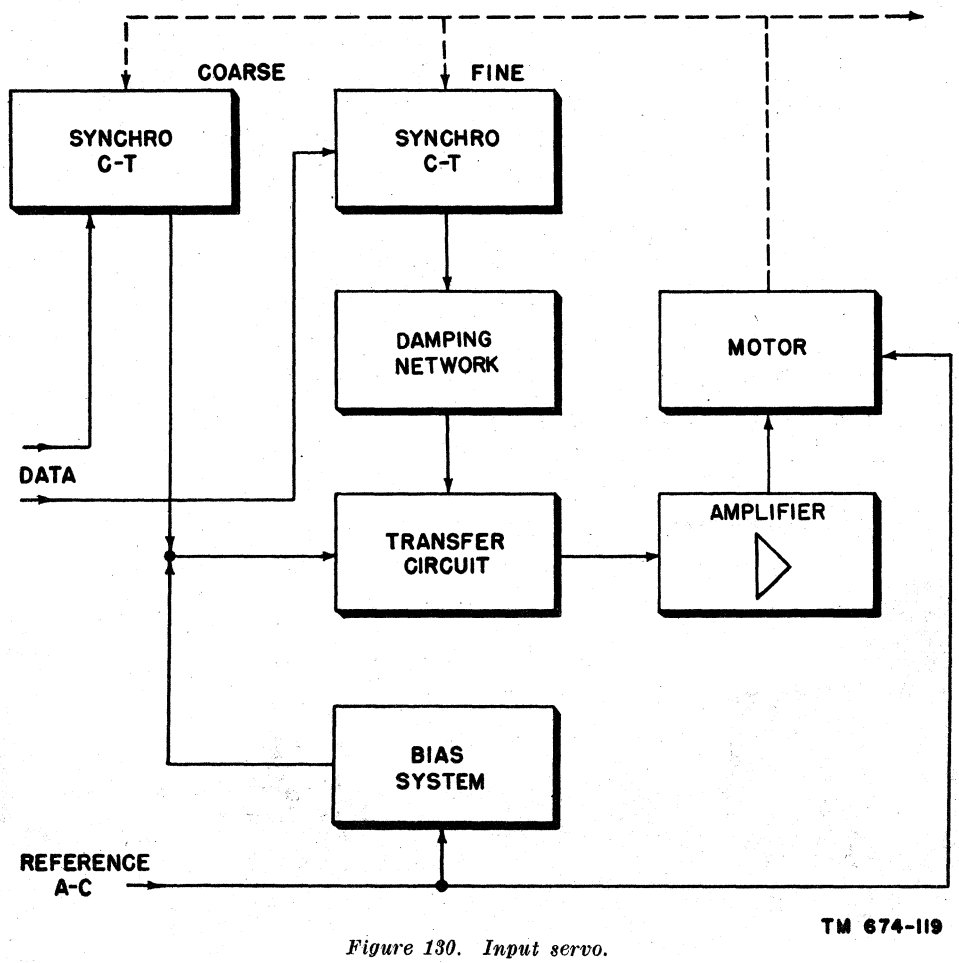


Figure 130. Input servo.

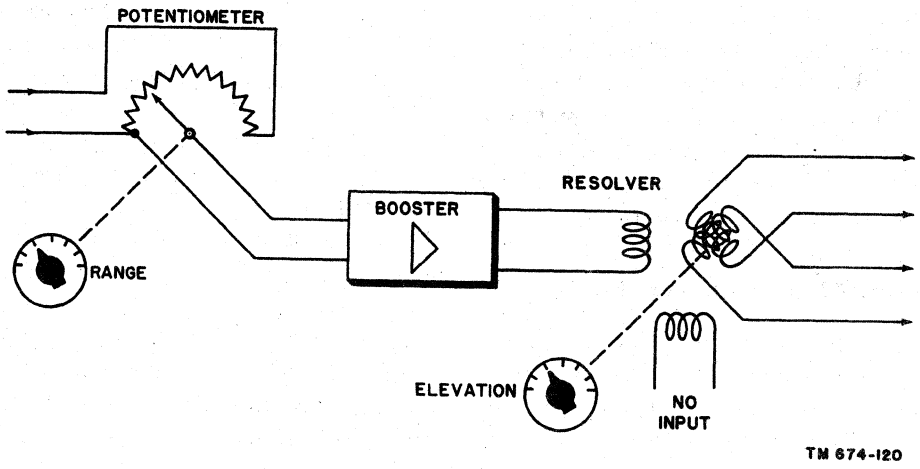


Figure 131. Conversion from present slant range and present elevation to present horizontal range and present height.

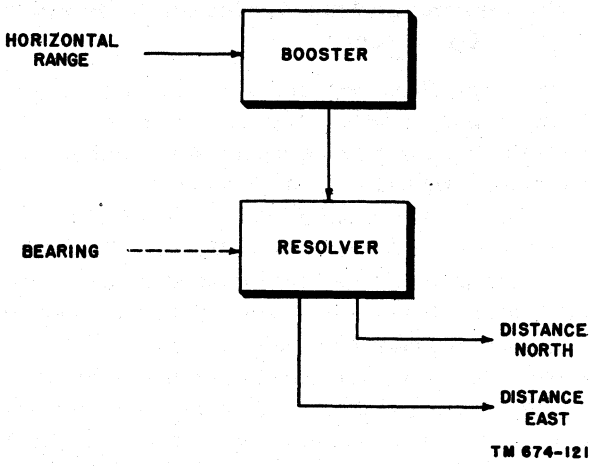


Figure 132. Conversion from horizontal range and present bearing to present distance north and present distance east.

a. Displacement Computation. The displacement is obtained as a voltage, the process being the same for each coordinate. A voltage proportional to the Cartesian rate is obtained from an induction generator carried on the present Cartesian-coordinate shaft (fig. 134). This excites a potentiometer which is set by a shaft called the displacement-time shaft. The displacement-time shaft is set by a servo, as discussed below, in obtaining the final solution. Since displacement time is the time required for the target to move from the present position to the future target position, choice of a displacement time is equivalent to choice of a future target position. For the moment, the output of the potentiometer is proportional to the product of the Cartesian rate by the displacement time and is a voltage proportional to the displacement.

b. Computation of Future Cartesian Coordinates. The Cartesian coordinates of the future target position are obtained by adding the displacement and the parallax correction to each of the present Cartesian coordinates. This is shown in figure 135, for one coordinate, and the circuits are the same for all three coordinates. A voltage proportional to the present Cartesian coordinate is obtained from an earlier section of the predictor (figs. 131 and 132). Another voltage proportional to the displacement is added to this, the displacement voltage having been produced in the section shown in figure 134. The result is a voltage proportional to the Cartesian coordinate of

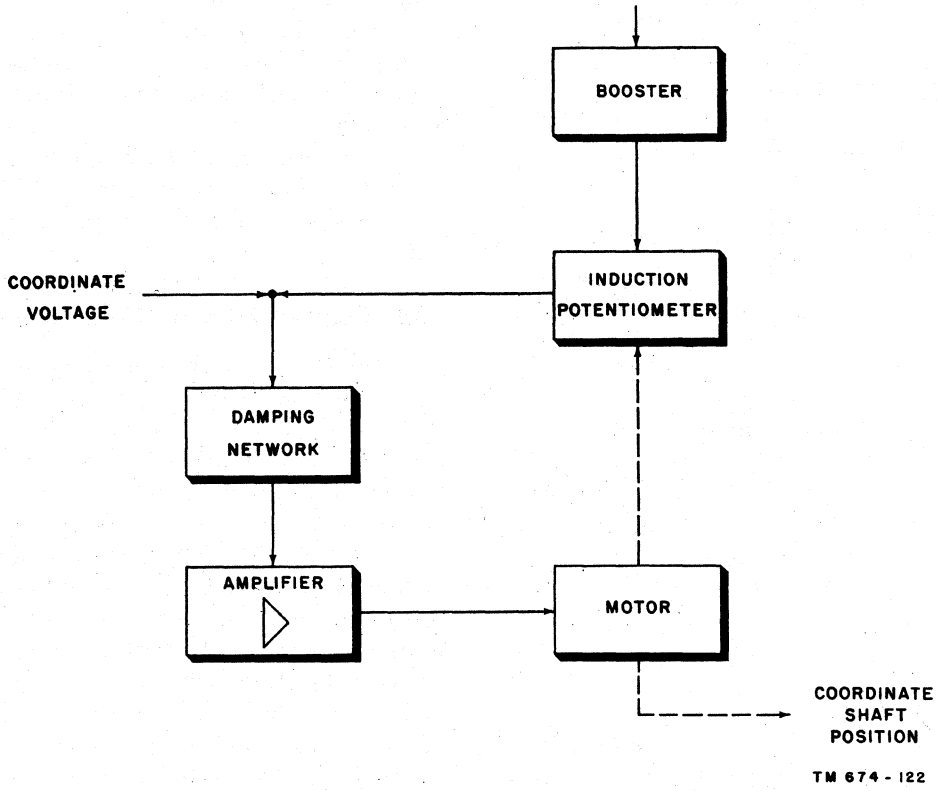


Figure 133. Conversion from voltage to shaft position.

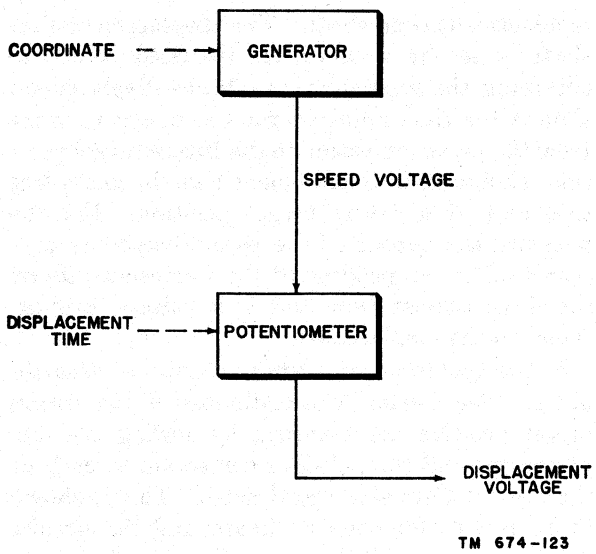


Figure 134. Displacement computation

the future target position relative to the radar. A voltage proportional to the parallax distance then is added to the sum to obtain a final voltage proportional to the Cartesian coordinate of the future target position relative to the gun position. The parallax voltage is obtained from a manually set potentiometer with fixed excitation.

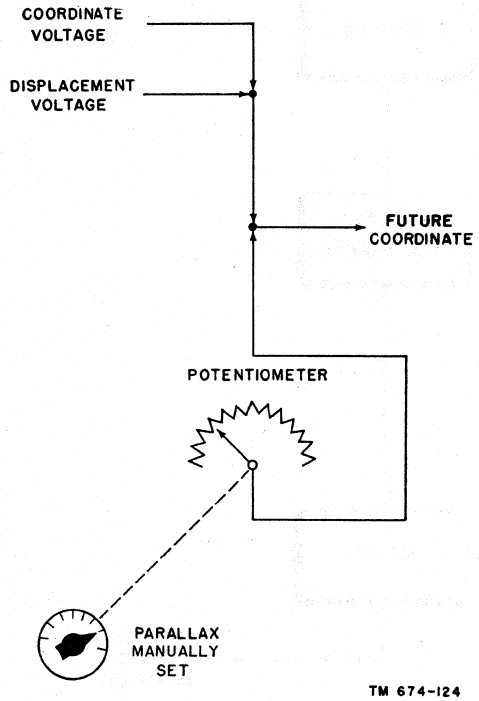


Figure 135. Computation of future Cartesian coordinate.

122. Conversion From Cartesian to Spherical Coordinates

Since the guns are pointed by alteration of the bearing and elevation angles, it is necessary to have the future target position in spherical coordinates, as described in *a* and *b* below.

a. Conversion From Distance North and Distance East to Bearing and Horizontal Range. Voltages proportional to future distance north and future distance east are fed to two booster amplifiers which excite the two primaries of a resolver (fig. 136). The output of one secondary of the resolver is passed through a damping network and a variable-gain amplifier to the input of a motor amplifier. It thus controls a servo motor which sets the resolver shaft to future bearing. The output of the other secondary of the resolver is a voltage proportional to future horizontal range. A variable-gain amplifier is required so that the stiffness of the bearing servo will be independent of the horizontal range (par. 82*c*).

b. Conversion From Horizontal Range and Height to Slant Range and Elevation. The arrangement is identical with the one described in *a* above. Voltages proportional to future horizontal range and future height are fed to two booster amplifiers which excite the primaries of a resolver (fig. 137). This is servoed to produce future elevation as a shaft quantity and future slant range as a voltage.

c. Conversion of Slant Range From Voltage to Shaft Quantity. This conversion is identical with the conversion described in paragraph 119 (fig. 138).

123. Computation of Time of Flight

If the choice of the future target position is satisfactory, the displacement time will be equal to the time of flight of a shell to the future target position. To obtain a solution, it is necessary to compute the time of flight.

a. Equation for Time of Flight. The equation for the time of flight is complicated, but for the purpose of this discussion a simple expression is used. As a first approximation, the time of flight is proportional to the future slant range. This neglects the effects of gravity and air resistance, and a second term must be added to take account of these. The gravitational force that slows the shell is proportional to the sine of the future eleva-

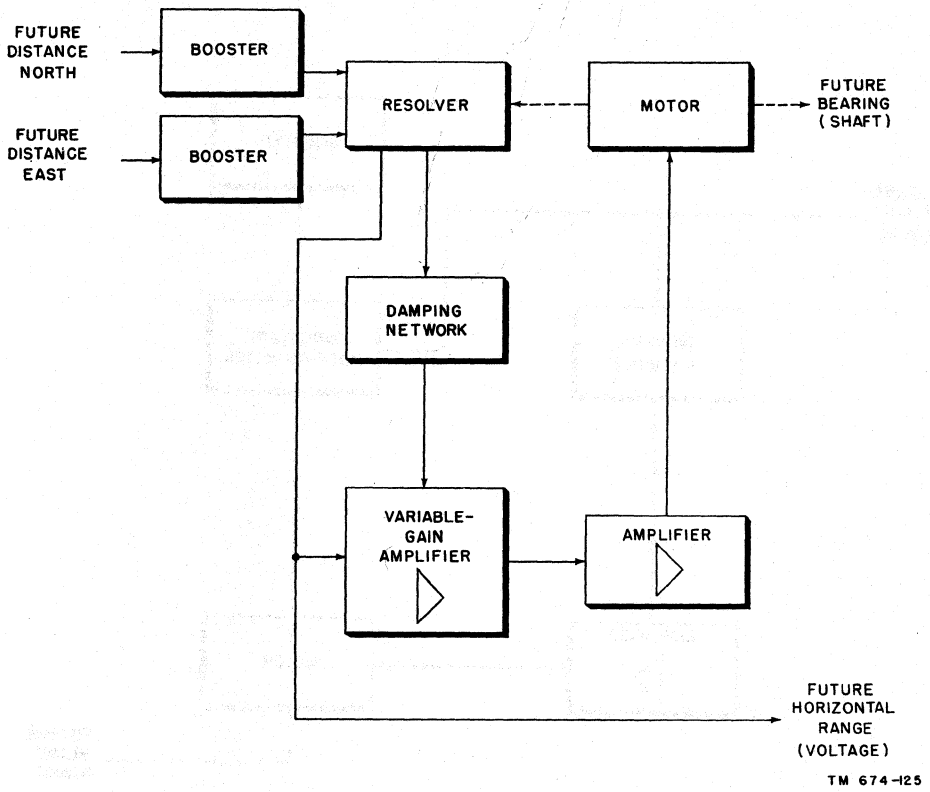


Figure 136. Conversion from future distance north and future distance east to future bearing and future horizontal range.

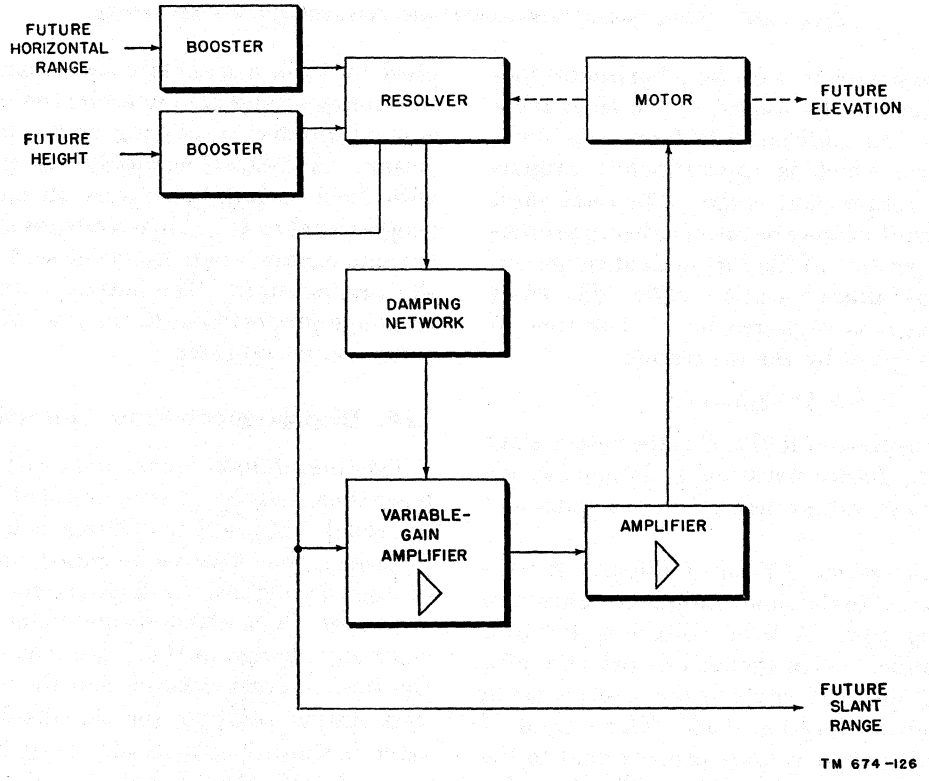


Figure 137. Conversion from future horizontal range and future height to future elevation and future slant range.

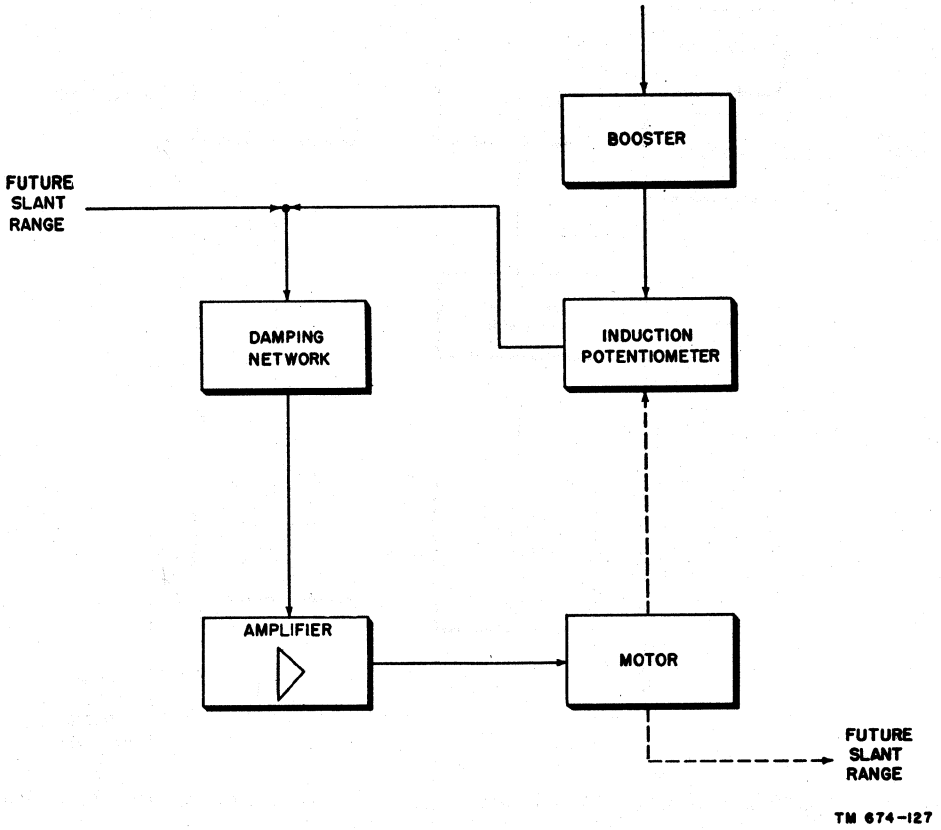


Figure 138. Conversion of future slant range from voltage to shaft setting.

tion angle, varying from zero for a horizontal shot to a force equal to the weight of the shell for a vertical shot. In addition, the force acts for a length of time which is approximately proportional to the future slant range. The total effect of gravity therefore may be taken as being proportional to the product of the future slant range and the sine of the future elevation angle. The effect of air resistance is neglected here. The time of flight then is given by the expression

$$T_f = k_1 R + k_2 R \sin E$$

where T_f is the time of flight, R is the future slant range, E is the future elevation, and k_1 and k_2 are constants whose values depend on the guns and ammunition.

b. Instrumentation of Time of Flight. A voltage proportional to the time of flight is obtained in the following way. A fixed voltage is fed to a booster amplifier which excites one primary of a resolver (fig. 139), the shaft of the resolver being set by the future-elevation shaft. One output of the resolver is then a voltage proportional to the sine of the future elevation angle. This is multiplied by k_2 in a manually set potentiometer, the sine voltage being used to excite the potentiometer and the product appearing as the potentiometer output. A second manually set potentiometer with fixed excitation delivers an output voltage proportional to k_1. These voltages are added and the sum excites a potentiometer set by the future-slant-range shaft. The output voltage of this is a voltage proportional to the time of flight to the future target position.

124. Displacement-Time Correction

The time of flight is compared with the displacement time, and the latter is adjusted if the two are not equal. If the time of flight is larger, the displacement time must be increased, and if the time of flight is smaller, the displacement time must be decreased. The elaborate predictor is necessary, since any change in the displacement time alters the future target position and the time of flight. The instrumentation for the displacement-time servo is shown schematically in figure 140. This servo must be slower than the others in the pre-

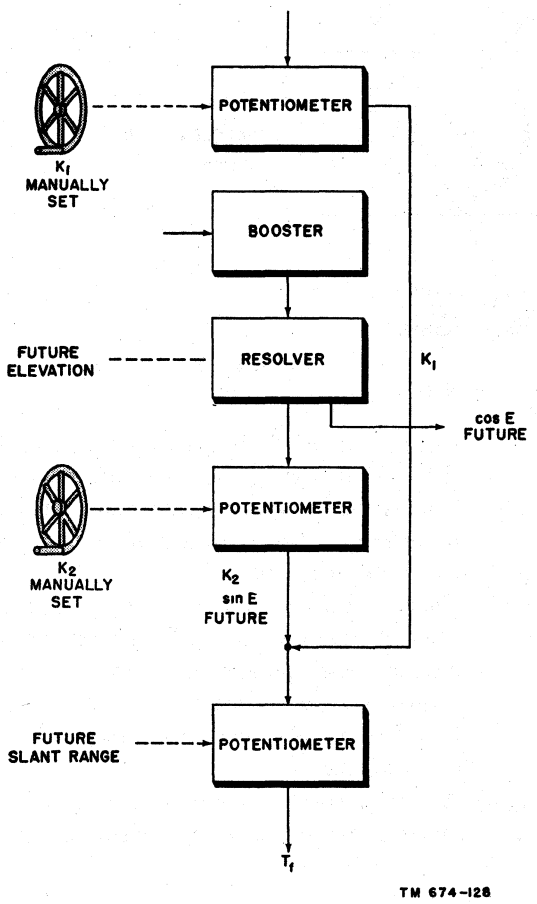


Figure 139. Computation of time of flight.

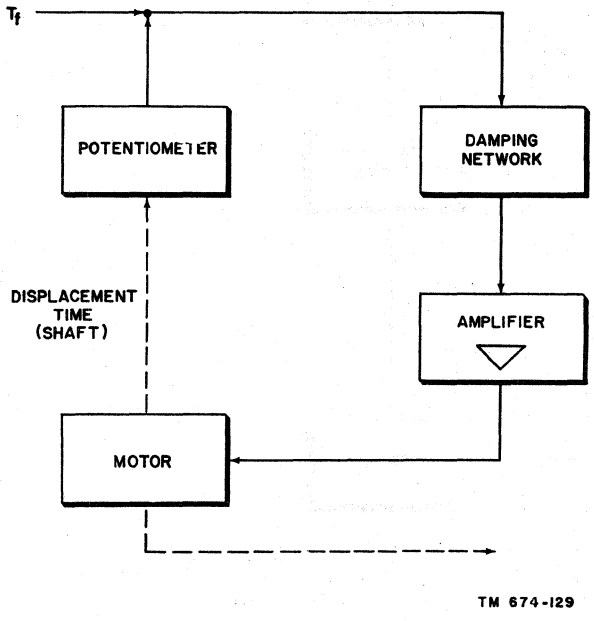


Figure 140. Displacement-time correction.

dictor, so that it acts to shift the displacement time only after proper time of flight has been computed on the basis of the existing value of the displacement time. It is usual to overdamp this servo and, in some cases, as the time of flight increases, a variable-gain amplifier is used to reduce the stiffness, which slows the servo when it is overdamped. The variable-gain amplifier is inserted between the damping network and the motor amplifier. The time-of-flight voltage is used as a control signal.

125. Superelevation Computation

When a solution has been obtained and a suitable future target position is determined, it is then necessary to develop gun orders. Because of the effect of gravity, the path of the shell drops below the line along which it is aimed. The gun then must be pointed not at the future target position, but at a point slightly above this. In practice, other corrections are required, but these are neglected in this discussion.

a. Equation for Superelevation. The effect of gravity in pulling the shell down is proportional to the range and to the cosine of the elevation angles. The superelevation angle is taken, for this discussion, as equal to $(k_3 R \cos E)$, k_3 being a constant whose value depends on the guns and ammunition, R the future slant range, and E the future elevation.

b. Instrumentation of Superelevation. This is handled in much the same way as the time of flight. A voltage proportional to the cosine of the future elevation angle is obtained from the resolver used in the time-of-flight computation (fig. 139). This is multiplied by k_3 in a manually set potentiometer and then by R in a potentiometer set by the future-slant-range shaft (fig. 141).

c. Conversion of Superelevation to Shaft Quantity. This conversion is similar to others in which voltages are converted to shaft positions, and is shown schematically in figure 142.

126. Predictor Output

The output of the predictor is synchro data for gun bearing and gun elevation. Gun bearing is the same as future bearing and is available as a shaft quantity. (This is not true in practice, but has been assumed here to simplify the discussion.) Gun elevation is the sum of future elevation and

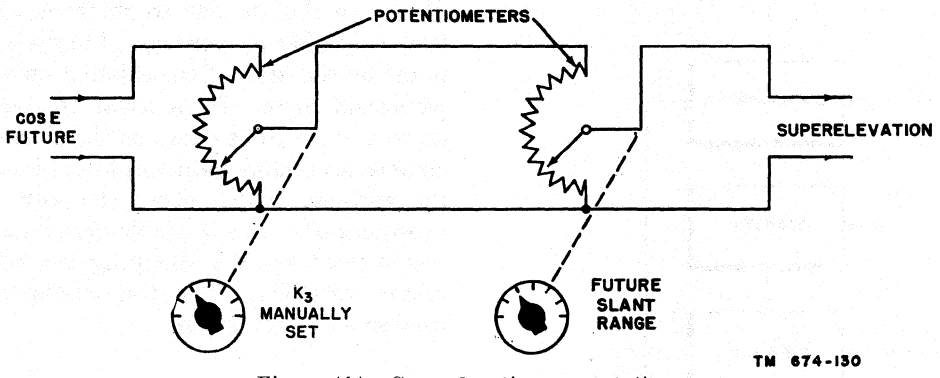


Figure 141. Superelevation computation.

superelevation. Both of these quantities are available in the form of shaft positions, and their sum is obtained by addition in a mechanical differential (fig. 143). The final-output shafts set coarse and fine synchros, and the synchro data are sent to the guns controlled by the predictor. Servos at the guns position them in accordance with the gun orders.

127. Summary and Review Questions

a. Summary.

(1) One application of servo systems is illustrated by the operation of a thermostatically controlled oil-burning furnace, the thermostat serving as a sensing element. The system may be made more efficient by adding a heating element which provides stepwise control.

(2) Servo followers and receivers often are used in conjunction with synchro transmitters on ships and aircraft to provide high-precision compass readings at points some distance away from a master compass.

(3) An important military application of servos is in conical-scan radars, in which

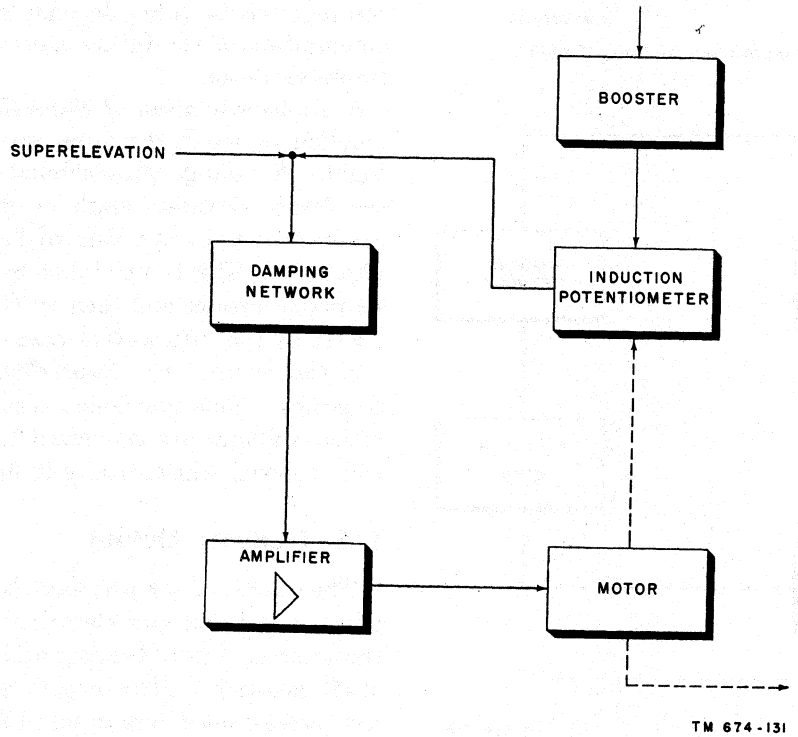


Figure 142. Conversion of superelevation from voltage to shaft quantity.

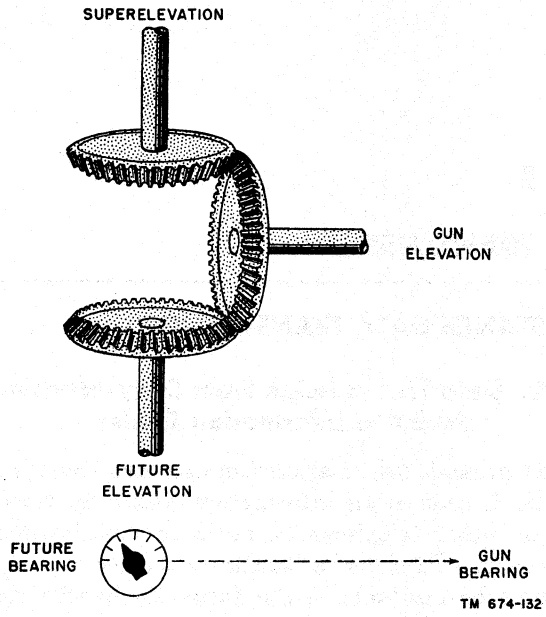


Figure 143. Predictor output.

an azimuth servo and an elevation servo position the radar antenna so that the target lies on the radar line of sight. Echoes from a single target are selected by a range gate, and filtered to obtain a varying voltage proportional to the echo strength. The amplitude of the a-c component of this voltage indicates the amount by which the target is off the radar line of sight; the phase indicates the direction. This a-c component is called the error voltage. The error voltage is fed through two commutator circuits and a d-c amplifier to excite the field of an amplidyne. The amplidyne acts as controller for a d-c servo motor which positions the antenna. Synchro systems, utilizing coarse and fine elements, are used to transmit changing antenna positions to the predictor, and make possible remote control of the antenna.

(4) An antiaircraft predictor receives a continuous flow of position data from the radar, in terms of slant range, angle of elevation, and azimuth or bearing. These values are combined with a displacement time, determined by the rate of change of the position data, to compute a future target position. Corrections for time of flight, superelevation, and parallax are added to provide gun orders in terms of bearing and elevation. These data are sent by synchro systems to positioning servos at the guns.

b. Review Questions.

(1) Explain why stepwise control is more advantageous in heating a house than the on-off system.

(2) What is a compass repeater servo and why is it used?

(3) Explain the difference between azimuth and bearing.

(4) What are the three coordinates used in tracking?

(5) How far will radio waves travel in 1 microsecond?

(6) Why are an amplidyne drive and a d-c servo motor preferred for conical-scan antennas?

(7) Name at least four servo components used in a synchro system.

(8) What are the three Cartesian rates?

CHAPTER 5

LONG-DISTANCE DATA TRANSMISSION

Section I. REQUIREMENTS FOR LONG-DISTANCE DATA TRANSMISSION

128. Designation of Target for Tracking Radar

In general, a tracking radar is advised of the approximate position of a target. It then searches for the target and, when the target is found, begins to track. As soon as the radar starts tracking, the associated predictor starts to develop a solution, and in a short time gun orders are available. As target speeds increase, however, there is a decrease in the firing time remaining after the target has been found and the solution has been obtained. One way of obtaining more firing time is to shorten the time required to find the target and obtain a firing solution. This can be accomplished by sending more precise data to the radar. It can then start tracking on the external data so that it is pointing in almost the right direction when the target comes in view. Because the radar is already tracking, the predictor will have an approximate solution when the target comes in view, and a precise firing solution can be obtained after a fairly short tracking period. This method of increasing the firing time requires that fairly precise data be sent over relatively long distances.

129. Data Transmission From Early-Warning Radar to Information Center

At present, information from an early-warning radar is sent to an information center by voice, using either telephone or radio communications channels. In order to handle data more rapidly, it may be desirable in the future to handle the transmission automatically. Ranges and bearings of targets observed at the early-warning radar then may be converted to Cartesian coordinates in respect to some convenient origin, which will probably be the same for all radars associated with a given information center, and transmitted automatically to the information center. Again, long-distance data transmission methods will be required.

130. Utilization of Data From Remote Tracking Radar

In the event that enemy aircraft are engaged by long-range missiles, it will be necessary to send precise position data from a tracking radar to the missile-launching site so that the target velocity can be determined and proper missile-launching orders can be computed. This, too, will require long-distance data transmission methods.

Section II. BASIC PROBLEM

131. Normal Data Transmission

For best results, voltage data transmission, with the exception of that used in computers, involves repeating the position of a shaft at a remote point. This normally is done with the aid of synchros, the synchro data being transmitted from one point to the other on transmission lines. When space requirement is not important, transmission of shaft position can be accomplished more easily by means of resolvers than by using synchros, since the former require only two subchannels each, but can otherwise be used exactly like synchros, in coarse-fine arrangements, without boosters. Potentiometers, too, can be used, but they are objectionable for many reasons, as explained in paragraph 87. Since synchros usually are preferable, the following discussion of data transmission over wire lines is by means of synchros.

132. Nature of Synchro Signals

Synchro signals consist of alternating current at varying amplitudes, usually at a frequency of 60 cps. As a synchro turns through a complete revolution, the signal on each of its output leads passes through a complete amplitude cycle, falling to zero, rising to a maximum amplitude with reversed phase, falling again to zero, and returning to its original level with its original phase (and, at some point, passing through a maximum with its original phase). Data transmission by conventional methods thus is reduced to the problem of transmitting 60-cps signals of varying amplitude.

133. Effect of Long Transmission Lines

Some effects of long transmission lines, whether wire lines or involving telephone or radio links, are, first, they mix up the signals because of crosstalk between the lines; second, they add noise to the signals; third, they treat the various signals in slightly different ways so that the amplitude relations between them at the receiving end are not the same as those at the sending end; and fourth, they do not pass 60 cps. Any of these effects can spoil the accuracy of data transmission signals over a long distance.

Section III. SYNCHRO DATA TRANSMISSION OVER VOICE CHANNELS

134. Subcarrier Transmission

The simplest way to send synchro signals over a long distance without tying up a separate channel for each signal is to use subcarrier transmission over one or more voice channels. A number of distinct audio frequencies are selected as subcarriers. Each of these then is modulated by a single synchro signal, either by amplitude or frequency modulation. The several modulated audio signals then are added and the sum is sent as a voice signal over a wire line or used to modulate a voice channel in a radio communications link. At the receiving end, the several subcarriers are separated by filters and detected in the usual way (either by amplitude-modulation detectors or by frequency-modulation discriminators) to recover the original synchro signals. This method is good in respect to balanced treatment of the several signals and also in respect to elimination of crosstalk (the effect of one signal on another). It is poor, however, from the standpoint of contamination of the signals by noise, the lack of bandwidth, and the large number of channels required. Sending coarse and fine synchro data for three coordinates requires 19 channels—18 for the synchro outputs and 1 for the a-c excitation signal required for a reference. It should be pointed out that 13 subchannels would be required for resolver transmission of 3 coordinates on a coarse-fine basis.

135. Effect of Noise

Since synchro data depend on the relative amplitudes of the three outputs of each synchro, the addition of noise reduces the available accuracy by limiting the precision with which the signal amplitudes are known. In addition, since the synchros at the receiving end are normally control transformers feeding repeater servos, the effect of noise reduces the precision with which the servos set the repeater shafts, as explained in paragraph 19.

136. Effect of Bandwidth

a. A narrow bandwidth is desirable for each of the channels in the synchro transmission system, both to reduce contamination of the signals by noise and to reduce the total space required in the available frequency spectrum for transmission of a given number of synchro signals. Narrowing the bandwidth of a transmission system, however, produces a number of undesirable effects. If a band-pass filter is added at the output of the control transformer at the receiving end, it becomes a part of the servo loop of the repeater servo, and although such a filter will reduce the noise level in the servo system, it also will introduce a certain amount of integral control which is antidamping, as explained in paragraph 65. If the band-pass filters are introduced in the transmission channels where they operate directly on the synchro output signals, they will produce lag in the transmission (in much the same way that a resonant circuit tends to ring) so that the repeater shaft will follow with a velocity lag.

b. At first glance, it appears that improved

accuracy can be obtained by using a higher gear ratio for the fine synchro, so that a given synchro error produces a smaller error in the position of the repeater shaft. Unfortunately, this improvement is obtained at the expense of increased bandwidth requirement for the fine synchro signals, since the 60-cps output of the synchro changes more rapidly with changing shaft position when its gear ratio is increased. In general, improving the system accuracy, whether by reducing the noise with filters or by increasing the gear ratio of the fine synchros, introduces velocity lag. There is, therefore, a choice between obtaining good static accuracy accompanied by the undesirable velocity lag when using a narrow bandwidth, or obtaining poor static accuracy and somewhat less velocity lag when using a wide bandwidth. The effect is seen most clearly when the band-pass filter is added at the output of the receiving control transformer. The reduction of noise improves the static accuracy. The band-pass filter is, however, antidamping and, if additional viscous damping is added to restore stability, introduces velocity lag. It is not possible to use error-rate damping without getting velocity lag because the error-rate damping network is essentially a band-stop filter and precisely cancels the noise-reduction effect of the band-pass filter.

Section IV. PULSE-CODE MODULATION

137. Basic Pulse-Code Modulation Theory

The basis of pulse-code modulation is the ending of a signal as a group of pulses. Each pulse is either present or absent, and neither the amplitude nor the duration of a pulse conveys information. If the pulses are sufficiently above noise level, there is little chance of either missing a pulse that is present or mistaking noise for a pulse that is absent. The pulse-code modulation system described in this section, which is designed for transmitting shaft-position data, is not like any system in use but will, nevertheless, serve to illustrate the principles of pulse-code modulation.

a. Representation of a Number by a Group of Pulses. Any number can be represented by a group of pulses. A specific number is assigned to each pulse, and the number represented by the group is the sum of the numbers corresponding to these pulses that are present. The smallest number of pulses for a given range of numbers is obtained when one of the pulses has a value of 1, and others have values of 2, 4, 8, 16, and so on. This allows representation of the numbers 0 through 7 by a group of three pulses (fig. 144), and representation of the numbers 0 through 1,023 by a group of ten pulses.

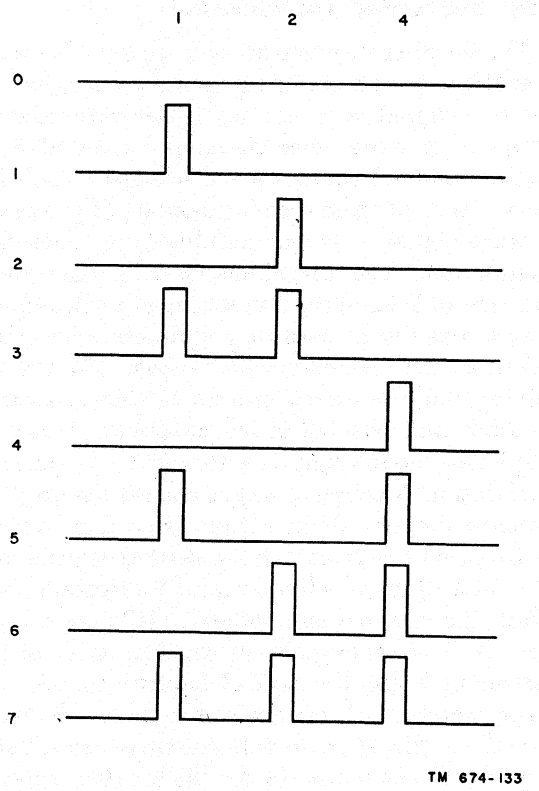


Figure 144. Representation of numbers by pulse groups.

b. Transmission of Successive Numbers. Information about a varying quantity can be sent by successive transmission of numbers associated with the quantity. For example, a varying shaft position can be sent by transmitting a dial reading several times a second. Speech, for example, can be sent by converting the audio-voltage level to a number and transmitting successive numbers at about 8,000 numbers per second. Although this may appear difficult by comparison with conventional amplitude- or frequency-modulation methods, it is not particularly troublesome when electronic techniques are used for the conversion. Fairly wide bandwidth is required, but the system

is almost completely free from noise contamination.

c. Merits of Pulse-Code Modulation. The chief merit of pulse-code modulation is its freedom from noise contamination when the transmission level is high enough for the pulses to stand out above the noise. The chief defects of the system are the relatively great bandwidth required and the fact that the data consist of successive samples rather than a continuous flow. Although a wide band is required, a large number of different signals can be sent at the same time over a single channel by a process known as multiplexing, which is described in paragraph 143. The fact that the data are not continuous occasions no difficulty if the samples are transmitted frequently enough.

138. Conversion From Shaft Position to Number

The present discussion is confined to the problem of transmitting shaft-position information by pulse-code modulation, although any quantity that can be converted to a number can be handled in the same way. Synchro voltages, for example, can be sent by pulse-code modulation, but it is simpler to make a direct conversion from shaft position to number without going through the intermediate step of converting to synchro data. The discussion in *a*, *b*, and *c* below describes equipment for direct conversion from a shaft position to a number. It is unlikely that such equipment would be used in practice, since it recognizes only eight possible positions for the shaft, but its principles are perfectly sound.

a. Shaft-Driven Switch. A shaft-driven switch (fig. 145) is nothing more than an eight-position shorting type switch. The term *shorting type* means that as the wiper moves it makes contact with each segment before breaking contact with the preceding segment, thus shorting the two segments together for a small interval. The segments of the switch are numbered 0 through 7. The wiper is connected to a positive d-c supply.

b. Switch-Reading Circuit. The circuit shown in figure 146 reads switch position 3. Similar circuits read the other seven switch positions. The tube normally is cut off by the bleeder resistor between B+ and the cathode. When the control grid is made positive by contact between the switch wiper and segment 3, the tube conducts,

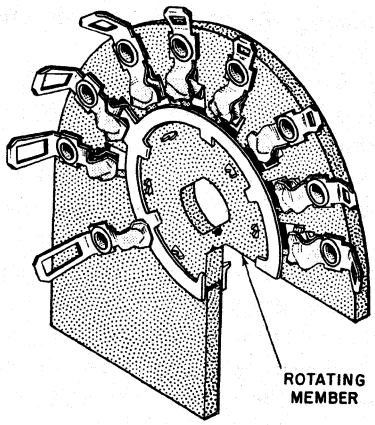


Figure 145. Shaft-driven switch.

unless segment 2 is in contact with the wiper at the same time. If both segments 2 and 3 are positive at the same time, the cathode is raised nearly to the level of the positive voltage to which the wiper is connected. The grid, however, is raised only a fraction of this amount because the two resistors connected to the grid form a voltage divider, and the tube does not conduct. The rectifier is added to prevent interaction between this switch-reading circuit and the one reading position 2. With the shaft in position 3, this tube draws current and the cathode rises. In the absence of the diode, this might raise the voltage of segment 2, to which the cathode is connected, sufficiently to cause the number 2 switch reader to conduct. This is impossible with the rectifier, however, because it looks like an open circuit when its cathode is more positive than its anode. At the same time, the rectifier does not affect the

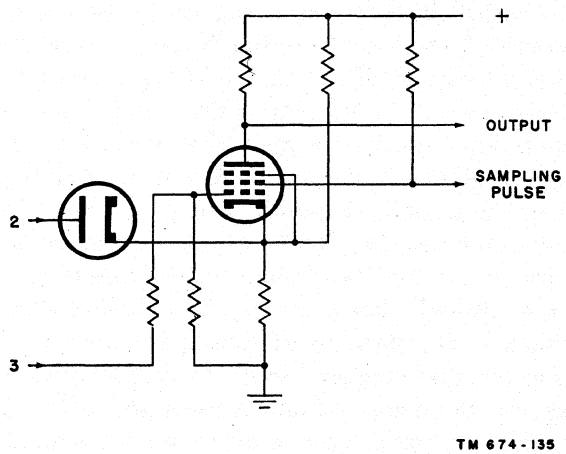


Figure 146. Switch-reading circuit.

operation of raising the cathode of this circuit when segment 2 is positive.

c. Necessity for a Complex Switch System. Unless something like the switch reader described above is used, the shaft position is uncertain when two segments of the switch are connected to the wiper at the same time. The situation is not improved by the use of a nonshorting switch, for then there is no information about the shaft position when the wiper is between segments. There is, however, no uncertainty with this reading system. The switch-reading circuits see the shaft position 3 whenever the wiper is in contact with segment 3 alone or with segments 3 and 4.

139. Coding the Number

The shaft position is converted to a number by applying a negative pulse simultaneously to the screen grids of all switch-reading tubes. In the tubes that are cut off, no change results from the negative screen pulse. In the conducting tube, however, the plate current is reduced and a positive pulse appears at the plate of the tube. There are, then, eight leads, one from the plate of each switch-reading tube. Whenever the shaft position is to be sampled, the negative screen pulse is applied to all tubes and a positive pulse appears on one of the eight lines. In practice, all the pulses in the pulse group are absent when the shaft is in position 0. It is therefore unnecessary to include a switch-reading circuit for the 0 segment unless it is desired for checking performance. The number corresponding to the shaft position is converted to a pulse, as described in *a*, *b*, *c*, and *d* below.

a. 1-Group Connections. When the shaft position is read by applying a negative pulse to the screens of the switch-reading tubes, a positive pulse appears at one of the eight input resistors of the coding circuit (fig. 147). The 1-group connections are so arranged that the 1-bus receives a positive pulse at the instant of sampling when the shaft is in positions 1, 3, 5, or 7. As shown in figure 147, the 1-pulse is present in the pulse group for these numbers. Connection is made through diodes as in the switch-reading circuits. The purpose of this is to prevent an input pulse on number 1 input resistor from leaking over to number 3 input resistor and affecting the other output bus connected to number 3 input.

b. 2-Group Connections. The 2-group connections lead from input resistors 2, 3, 6, and 7 through rectifiers to the 2-bus.

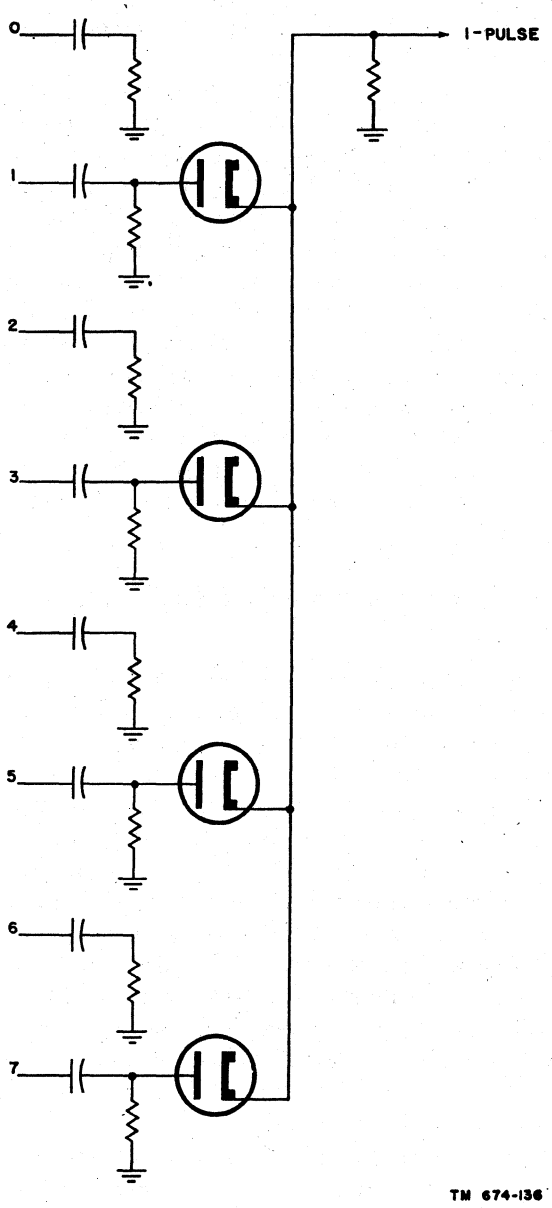


Figure 147. 1-Group connections.

c. 4-Group Connections. The 4-group connections lead from input resistors 4, 5, 6, and 7 through rectifiers to the 4-bus.

d. Complete Coding Connections. The complete coding connections are shown in figure 148. Inspection shows that an input pulse at any one of the input resistors 0 through 7 produces the appropriate pulse group on the output busses, and that there is no requirement for the 0 switch-reading circuit. The plate of each of the switch-

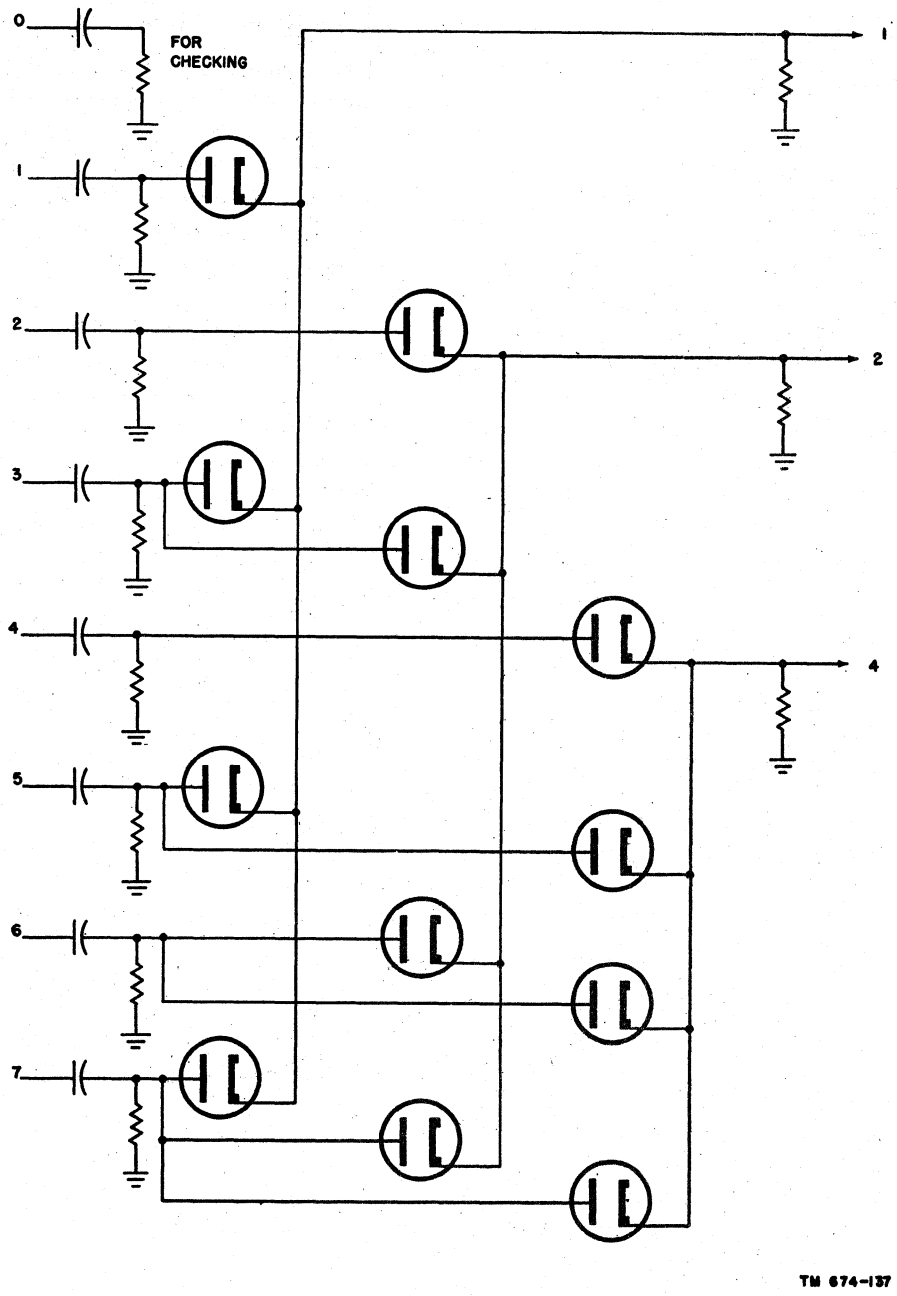


Figure 148. Complete coding connections.

reading tubes is connected, through the blocking capacitor, to the corresponding input resistor of the coding network; at the instant of sampling, the input pulse corresponding to the shaft position is obtained at the appropriate input resistor. The output busses, therefore, carry the proper pulse group as a series of positive pulses, present or absent, appearing simultaneously shortly after the negative sampling pulse is applied to the screen grids of the switch-reading tubes.

140. Reading the Coder

At frequent intervals, the system is read. That is, a sampling pulse is applied to the switch-reading tubes, and the pulse group corresponding to the shaft position appears on the output busses

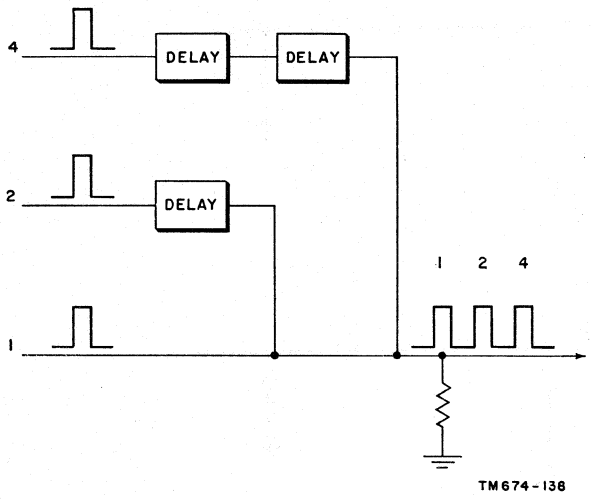


Figure 149. Delay lines for conversion from parallel to serial pulse group.

of the coder. The pulse group then may be sent to a remote point over any conventional communication system.

a. Parallel Reading. In parallel reading, the several output pulses from the coder are used as they appear, simultaneously on separate busses.

b. Serial Reading. In many applications, it is desirable to have the pulses, when they are present, appear serially one after another on a single line, rather than simultaneously on separate lines, in parallel. A circuit for accomplishing this is shown in figure 149.

141. Data Transmission

The several pulses in the pulse group can be sent simultaneously over separate channels, but normally are sent one after the other over a single channel. If they are sent on a single channel, it is necessary to precede the pulse group by a synchronizing pulse, usually of greater duration than the single pulses. Without the synchronizing pulse, it is not possible to read the pulse group. For example, it is not possible to distinguish between 1, 2, and 4 since each consists of a single pulse. With the synchronizing pulse, however, the 1-pulse, if present, arrives at a definite time after the synchronizing pulse and the same thing is true of the others; 1, 2, and 4 then are distinguishable by the difference in the time interval between the synchronizing pulse and the signal pulse.

142. Data Reception

Data normally are transmitted as a synchronizing pulse followed by the information pulse group, which consists, in this case, of a group of three pulses (each of which may be present or absent). This series of pulses is picked up by receiving equipment at the remote point and passed to the data-receiving equipment, which sets the repeater shaft.

a. Synchronizing Pulse Recognition. One simple circuit which is able to recognize the synchronizing pulse is shown in figure 150. Each incoming pulse is passed to both grids of the tube, directly to one and through the delay line to the other. With information pulses, which are short, the direct pulse will be completed at one grid before the delayed pulse arrives at the other. There will, therefore, be no current. In the synchronizing pulse, which is longer, there will be a short period during which both grids are positive and the tube will conduct. On receipt of the synchronizing pulse, the circuit delivers a negative pulse at the tube plate.

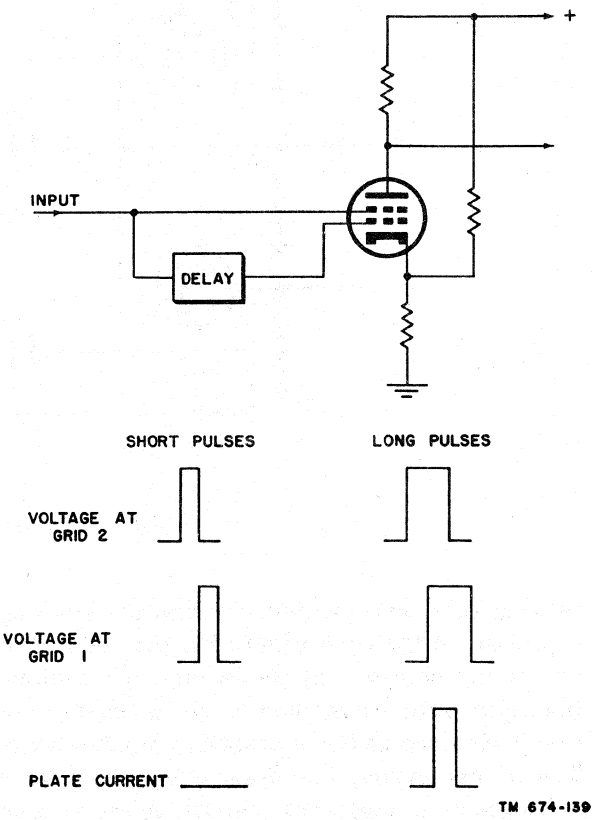


Figure 150. Synchronizing-pulse recognition circuit.

b. Repeater-Shaft Position Sampling. As soon as the synchronizing pulse is received, a negative sampling pulse is sent to the screen grids of the switch-reading tubes associated with the repeater shaft. The output pulse from these is passed to a coder and the resulting pulse group is passed through a delay network to provide a serial pulse group similar to the pulse group which is received.

c. Pulse-Group Comparison. All of the required information is now present. The received pulse group gives information about the position of the transmitting shaft; the local pulse group gives information about the position of the repeater shaft. The received pulses are reshaped so that they have proper duration and amplitude, and both groups are fed to a differential amplifier (fig. 151). A received pulse alone causes the amplifier to deliver a positive output pulse. A local pulse alone causes it to deliver a negative output pulse. Both together do not cause any output, nor does either one alone. The output of the differential amplifier is then a set of three pulses, each being either positive, negative, or absent. This set of pulses indicates the error in the receiver-shaft position if positive pulses are taken as positive numbers and negative pulses as negative numbers. It does this because it is equal to the difference between the numbers represented by the two pulse groups. Thus, for example, if both 1-pulses are present or absent, there is no output from the differential amplifier. If only the incoming pulse is present, the positive output indicates a difference of plus 1; if only the local pulse is present, the negative output indicates a difference of minus 1.

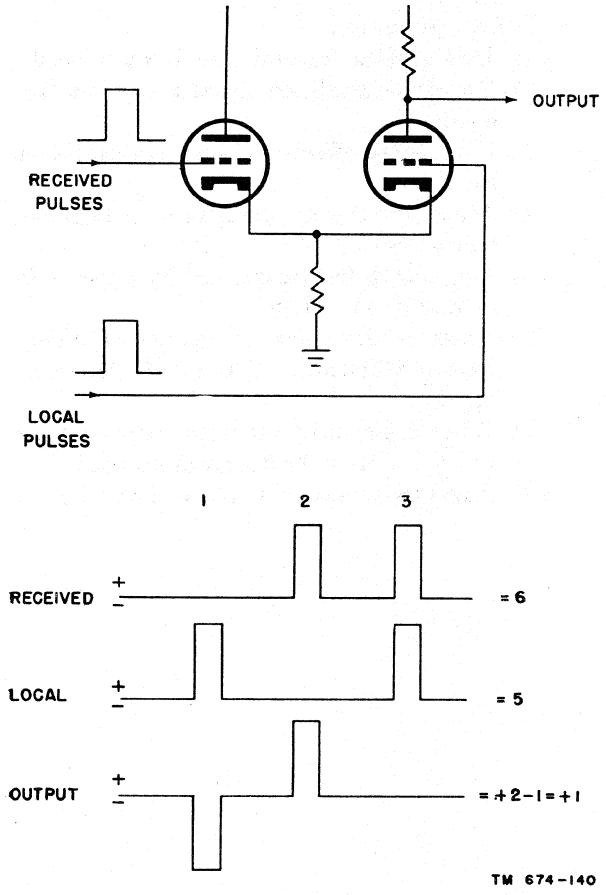


Figure 151. Pulse-comparison circuit.

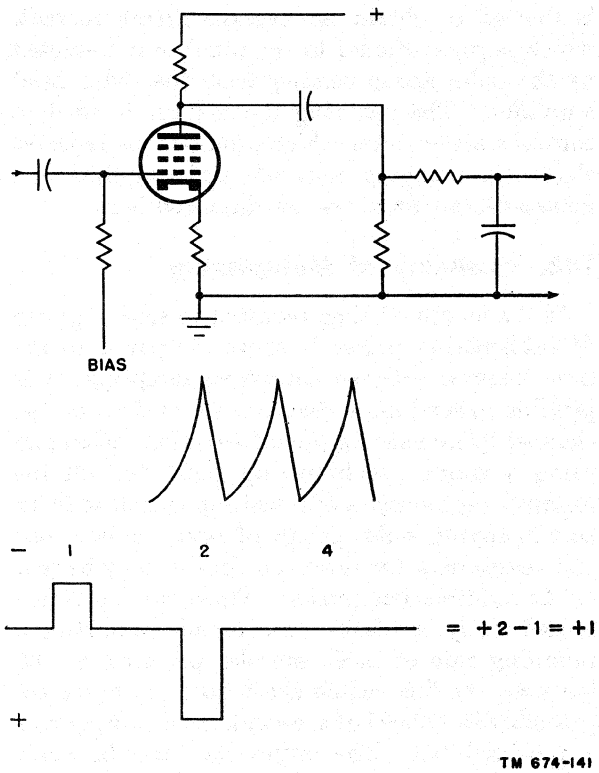


Figure 152. Variable-gain amplifier circuit.

d. Signal to Servo Motor. The pulse group from the differential amplifier now goes to a variable-gain amplifier (fig. 152), a pentode with a variable bias. The gain is initially low and starts to rise immediately after the synchronizing pulse is received, doubling during the interval between successive information pulses. The result is that a positive or a negative 1-pulse delivers a certain output, while a positive or a negative 2-pulse delivers twice the output, and a 4-pulse delivers four times the output. The resulting set of pulses then

is filtered to obtain an average direct current, which is proportional to the number represented by the pulse group coming from the differential amplifier. The resulting d-c voltage is used to control a servo motor which positions the repeater shaft. A damping network and amplifier are necessary, but these are not discussed here.

143. Possibility of Multiplexing

If the length of time required to send a group of information pulses is short compared to the time interval between successive sampling, it is possible to send more than one set of data on the channel by interlacing the information pulses and using a single synchronizing pulse for all the groups. Assuming a 128-position switch with an accompanying pulse group of seven pulses, fine and coarse data for three coordinates may be sent by 42 information pulses. These can be transmitted easily in 1/2,000 of a second, permitting a sampling rate of 2,000 samples per second. If, however, the fine switch shaft does not move appreciably in 1/2,000 of a second, the sampling rate can be reduced. The pulses then can be made longer, thus reducing the required bandwidth, or additional information can be carried on the channel.

144. Summary and Review Questions

a. Summary.

(1) The use of long-distance data-transmission systems enables early-warning radars to send position data to a predictor before the target comes into view, thus materially decreasing the time required for computation of a predicted position and gun orders.

(2) All types of long transmission lines are adversely affected by crosstalk, noise, and unequal treatment of the amplitudes of different signals.

(3) Subcarrier transmission over voice channels is the simplest method of sending synchro signals over a long distance. However, this system of transmission is subject to several undesirable effects—for example, poor static suppression and velocity lag.

(4) Pulse-code modulation offers many advantages as a method of long-distance data transmission, since it is relatively free from noise contamination. A wide bandwidth is required, but many signals may be sent over a single channel by multiplexing. The transmitted data are compared with the position of the repeater shaft by a differential amplifier, and the result fed through a variable-gain amplifier and a filter circuit to a servo motor which positions the repeater shaft.

b. Review Questions.

(1) How is data transmission accomplished?

(2) Synchro signals are usually at what frequency?

(3) Give three effects of long transmission lines.

(4) What are the advantages of subcarrier transmission?

(5) Can speech be transmitted by pulse-code modulation? How?

(6) What is the chief advantage of pulse-code modulation? The chief disadvantage?

(7) What is meant by the term *shorting-type* as used with a shaft-driven switch?

(8) Name two ways of reading the coder.

INDEX

	Paragraphs	Page
A-c damping network	64*b*	55
A-c integrating network	65*b*	56
A-c motor	48	30
A-c, d-c motor	47	30
Acceleration error	34	22
Acceleration generator	97	80
Acceleration lag	22	18
Actuator	12*b*	8
Hydraulic	49	34
Solenoid	50*a*	36
Amplidyne drive, for d-c motors	53	40
Analogue computer	114	95
Antenna servo signals	111	90
Antiaircraft:		
Computation	121*a*	99
Conversion	118*a*	96
Input data	117	96
Position data	118	96
Predictor	116	96
Antibacklash devices	51	37
Armature control	46*c*	28
Automatic servo	7*b*	4
Automatic servo loop	7*b*	4
Automatic tracking	9	6
Backlash	51	37
Booster amplifier	83	73
Application	83*b*	74
Theory	83*a*	73
Cartesian coordinates	121	97
Chopper:		
Mechanical	60*a*	47
Vacuum-tube	60*b*	48
Circuit:		
Amplidyne	53*a*	40
D-c synchro	88	77
Differential-amplifier	67*b*	58
E-transformer	91	78
Induction-generator	96	80
Linear-control transformer	92	79
Magnetic-amplifier control	57	45
Mechanical-chopper	60*a*	47
Microsen	90	78
Parallel-addition	67*c*	58
Pulse-comparison	142*c*	113
Rectifier-commutator	61*c*	51
Rectifier-modulator	60*c*	48
Rectifier transfer	63*c*	53
Relay transfer	63	52
Saturable-reactor control	56*b*	44
Series-addition	67*d*	59
Switch-reading	138*b*	109
Synchronizing-pulse	142*a*	112
Synchronous-switch	61*a*	50
Thyratron control	54*b*	43
Circuit—Continued		
Transfer	20*b*	17
Torque limiter	112*b*	92
Vacuum-tube:		
Chopper	60*b*	48
Commutator	61*b*	50
Control	55	43
Transfer	63*b*	52
Variable-gain amplifier	62, 142*d*	51, 113
Vibrating-reed comparator	67*a*	58
Ward-Leonard	52*b*	39
Closed-control system	5*c*	3
Coarse-fine control system	20*a*	20
Coder, parallel and series	140	111
Commutator	61	48
Vacuum-tube	61*b*	50
Compass repeater:		
Description	107	86
Use	108	86
Computer:		
Analogue	114	95
Digital	114	95
Multiplication	115	95
Conical-scan radar	110	87
Range gate	110*b*	88
Scanning	110*c*	89
Theory	110*a*	87
Constant-rate input	24	19
Contact head	93	79
Control:		
Armature	46*c*	28
Field	46*d*	28
Methods	14, 30	9, 22
On-off	14a, 35	9, 23
Proportional	14*c*, 37	10, 23
Stepwise	14*b*, 36	10, 23
Controller	12*c*	8
Hydraulic	58	46
Control system:		
Closed	5*c*	3
Coarse-fine	20*a*	16
Need	4	2
Open	5*a*	3
Open and closed	5	3
Conversion	106	85
Coordinate conversion	81*c*, 82, 82*c*	70, 71, 72
Coordinates:		
Cartesian	121	97
Plane	81	70
Plane Cartesian	81*a*	70
Polar	81*b*	70
Coupling, springy	42	24

	Paragraphs	Page
Damping	16	12
Error-rate	21*c*	18
Mechanical	94	79
Networks	64	55
Viscous	16*a*	12
Data transmission	129	106
Normal	131	106
D-c:		
Damping network	64*a*	55
Integrating network	65*a*	56
Motor	46	26
D-c generator	52, 95	38, 79
Theory	52*a*	38
D-c motors	46	26
Basic theory	46*a*	27
Split-field series	46*e*	29
D-c synchro	88	77
Dead space	18	14
Noise effect	19	16
Differential amplifier	67*b*	58
Digital computation	114	95
Dither	18*b*	14
Drive:		
Magnetic-clutch	59*a*	46
Steel-tape	59*b*	47
Error-rate damping	21*c*	18
Error-voltage:		
Commutation	111*b*	90
Waveform	111*a*	90
E-transformer	91	78
Field control	46*d*	28
Follow-up	12*d*	8
Generator acceleration	97	80
Hunting	15	12
Hydraulic:		
Actuator	49	34
Controller	58	46
Ram	49*b*	36
Induction generator	96	80
Integrating networks	65	56
Jamming	9	6
Jitter	18*a*	14
Linear-control transformer	92	79
Lost motion	43, 51	24, 37
Magnetic-amplifiers	57	45
Magnetic-clutch drive	59*a*	46
Mechanical:		
Chopper	60*a*	47
Damping	94	79
Integrator	98	80
Microsen	90	78
Microsen elastic-restraint motor	50*b*	37
Modulators	60	47
Motor:		
A-c	48	30
A-c, d-c	47	30
Motor—Continued		
D-c	46	26
Microsen elastic-restraint	50*b*	37
Preloading	51*a*	37
Split-field series	46*e*	29
Swash-plate	49*a*	34
Two-phase induction	48*f*	34
Multipolar fields	48*b*	31
Network:		
A-c damping	64*b*	55
A-c integrating	65*b*	56
Balanced damping	112*b*	92
D-c damping	64*a*	55
D-c integrating	65*a*	56
Open and closed control system	5	3
Open control system	5*a*	3
Order rate	21*b*	18
Oscillation	15	12
Overshoot	15	12
Parallel-addition circuit	67*c*	58
Plane Cartesian coordinates	81*a*	70
Plane coordinates	81	70
Polar coordinates	81*b*	70
Positioning loads	8	6
Positioning, precise	4*b*	2
Potentiometers	85	74
Design	86*b*	77
For data transmission	87	77
Induction	89	78
Resolution	86*b*	77
Types	86	74
Predictor	116	96
Output	126	103
Proportional control	14*c*, 37	10, 23
Proportional response	33	22
Pulse-code modulation:		
Coding	139	110
Coding connections	139	110
Conversion	138	109
Data reception	142	112
Data transmission	141	112
Merits	137*c*	109
Multiplexing	143	114
Pulse-group comparison	142*c*	113
Pulse recognition	142*a*	112
Sampling	142*b*	113
Switch-reading circuit	138*b*	109
Theory	137	108
Transmission of numbers	137*b*	108
Rectifier commutator	61*c*	51
Rectifier modulator	60*c*	48
Rectifier-transfer circuit	63*c*	53
Bias requirements	63*d*	53
Relay-transfer circuit	63*a*	52
Repeat-back	7*a*	4
Resolver	78	69
For data transmission	84	74
Response:		
ON-OFF	23*a*	19
Proportional	23*c*	19

	Paragraphs	Page
Response—Continued		
Sinusoidal	26	20
Step input	23	19
Stepwise	23*b*	19
Velocity-lag	26*b*	21
Viscous damping	26*a*	21
Rotating magnetic fields	48*a*	30
Rotors, types	48*g*	34
Saturable-reactor:		
Control for a-c motor	56	43
Control theory	56*b*	44
Theory	56*a*	43
Solenoid actuator	50*a*	36
Selsyn. (*See* Synchro.)		
Series-addition circuit	67*d*	59
Servo	2	1
Automatic	7*b*	4
Azimuth	112*c*	92
Definition	6	4
Elements	12, 28	8, 21
Elevation	112*b*	92
Examples	7	4
Loop	7	4
Operation	27	21
Proportional	18*d*	16
Stepwise	18*c*	16
System	2	1
Unstable	15	12
Slewing rate	25	20
Spherical coordinates	109	87
Split-field series d-c motor	46*e*	29
Split gearing	51*b*	38
Springy coupling	42	24
Steel-tape drive	59*b*	47
Stepwise control	14*b*, 36	10, 23
Stepwise response	23*b*	19
Superelevation:		
Computation	125	103
Conversion	125*c*	103
Equation	125*a*	103
Instrumentation	125*b*	103
Swash-plate motor	49*a*	34
Synchro:		
Bus designations	77*a*	67
Connections	77	67
Definition	69	59
Generator	70	59
Manual-control connections	113*b*	94
Remote-control connections	113*c*	95
Tracking connections	113*a*	94
Transmitter	70	59
Synchro-control transformer	72	63
Connections	77*d*	68
Description	72*a*	63
Operation	72*b*	63
Zeroing	75*c*	66
Synchro-differential receiver	74	65
Connections	77*f*	68
Description	74*a*	65
Operation	74*b*	65
Zeroing	75*e*	67
Synchro-differential transmitter	73	64
Connections	75*e*	67
Description	73*a*	64
Operation	73*b*	64
Zeroing	75*b*	66
Synchro receiver	71	61
Connections	77*c*	68
Description	71*a*	61
Operation	71*b*	61
Zeroing	75*e*	77
Synchro signals, nature	132	107
Synchro transmitter	70	59
Connections	77*b*	68
Descriptions	70*a*	59
Operation	70*b*	60
Output	70*c*	61
Zeroing	75*a*	66
Synchronous switch	61*a*	50
System:		
A-c and d-c	100	81
Antenna-positioning	112	91
Automatic temperature-control	102	84
Coarse-fine	20*a*	16
Remote control	7*c*	6
Servo	102	84
Synchro	113	93
Synchro motor	71	61
Thyratron:		
Control of d-c motor	54	42
For split-field d-c motors	54*b*	43
Theory	54*a*	42
Torque	45	26
Curves	46*d*, 48*f*	28, 34
Development	48*e*	32
In d-c motors	46*a*	27
Two-phase induction motor	48*f*	34
Tracking, automatic	9	6
Transfer circuits	20*b*, 63	17, 52
Transmission:		
Effect of bandwidth	136	107
Effect of long-line	134	107
Effect of noise	135	107
Subcarrier	136	107
Vacuum-tube:		
Chopper	60*b*	48
Commutator	61*b*	50
Control of a-c motor	55	43
Transfer circuit	63*b*	52
Variable-gain amplifier	62	51
Velocity lag	21	17
Response	26*b*	21
Vibrating-reed comparator	67*a*	58
Viscous damping	16*a*	12
Response	26*a*	21
Voltage-comparison methods	67	58
Ward-Leonard drive:		
For d-c motors	52	38
For servo	52*c*	40
Theory	52*b*	39
Zeroing procedure	75	65

☆ U. S. GOVERNMENT PRINTING OFFICE : 1955 O - 346232